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The Impact of Collaboration Between Science and Education Faculty Members on Teaching for Conceptual Change: A Phenomenographic Case Study of a Physics Professor

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ACCEPTANCE

This dissertation, THE IMPACT OF COLLABORATION BETWEEN SCIENCE AND EDUCATION FACULTY MEMBERS ON TEACHING FOR CONCEPTUAL CHANGE: A PHENOMENOGRAPHIC CASE STUDY OF A PHYSICS PROFESSOR, by WILLIAM A. STOLL III, was prepared under the direction of the candidate's Dissertation Advisory Committee. It is accepted by the committee members in partial fulfillment of the requirements for the degree, Doctor of Philosophy, in the College of Education and Human Development, Georgia State University.

The Dissertation Advisory Committee and the student's Department Chairperson, as representatives of the faculty, certify that this dissertation has met all standards of excellence and scholarship as determined by the faculty.

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PROFESSIONAL SOCIETIES AND ORGANIZATIONS

American Association of Physics Teachers (AAPT)

National Association of Research in Science Education (NARST)

THE IMPACT OF COLLABORATION BETWEEN SCIENCE AND EDUCATION FACULTY MEMBERS ON TEACHING FOR CONCEPTUAL CHANGE: A PHENOMENOGRAPHIC CASE STUDY OF A PHYSICS PROFESSOR

by

WILLIAM A. STOLL III

Under the Direction of Kadir Demir

ABSTRACT

This dissertation presents a phenomenographic case study of a senior physics professor during and beyond an extended collaboration with a science education professor from a College of Education. The context for the collaboration is the co-teaching of a physics course for graduate students in a Masters of Teaching program at a research university in the southeastern US. The course was focused on physics content and the pedagogy of *teaching for conceptual change*. The purpose of this study is to investigate from a physics professor's perspective the progression of his conceptions and practices regarding *teaching for conceptual change* over the duration of the collaboration and beyond. Prior research indicates that such change is a difficult and complex process requiring a transformative, personal experience. Collaboration between science departments and Colleges of Education has been identified as a key opportunity for transformative experiences, but research on the resulting changes is limited. Questions addressed by this study include (a) what is the evidence of change in a physics professor's conceptions of teaching for conceptual change, (b) what is the evidence of change in a physics professor's practices of teaching for conceptual change, (c) what are the learning environment characteristics identified by the physics professor that either facilitated or hindered changes in his conceptions and/or practices in teaching for conceptual change. The primary data were interviews with the physics professor integrated with direct classroom observations. Emergent categories of how the physics professor conceived and practiced teaching for conceptual change showed a progression over time toward a more expert view on teaching for conceptual change. Key factors identified in the physics professor's progression are: 1) his motivation to become a more effective teacher, 2) the expertise of the science education professor, and 3) the way the collaboration developed. Limiting factors identified include: 1) time pressure for content coverage, 2) difficulty in translating change to other contexts, and 3) unsupportive external environments.

INDEX WORDS: Teaching for Conceptual Change, Teacher learning, Teacher change, Collaboration, Phenomenography, Physics education, Teacher education, Undergraduate STEM instruction, Physics Education Research

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Dedicated to my mother and father, who have devoted their lives to service and whose faithfulness have blessed all; I am forever grateful for your love and encouragement.

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ABBREVIATIONS

AP	Advanced Placement
AAPT	American Association of Physics Teachers
AIP	American Institute of Physics
APS	American Physical Society
ACEPT	Arizona Collaborative for Excellence in the Preparation of Teachers
CBAM	Concerns-Based Adoption Model
DC	Domain of Consequences
DP	Domain of Practice
ED	External Domain
FCI	Force Concept Inventory
IRB	Institutional Review Board
IMTPG	Interconnected Model of Teacher Professional Growth
IB	International Baccalaureate
MAT	Masters of Arts in Teaching
NRC	National Research Council
NSF	National Science Foundation
PCAST	President’s Council of Advisors on Science and Technology
PRISM	Partnership for Reform in Science and Mathematics
PCK	Pedagogical Content Knowledge
PeD	Personal Domain
P-prims	Phenomenological primitive
PER	Physics Education Research

PHYS 1080	Undergraduate Studio Physics Course
PHYS 3000	Upper-level Science Lab Course
PHYS 7050	Physics Principles & Teaching Problems I
PhysTec	Physics Teacher Education Coalitions
PD	Professional Development
RBIS	Research-based Instructional Strategies
RTOP	Reformed Teaching Observation Protocol
STEM	Science, Technology, Engineering and Math
SPIN-UP	Strategic Programs for Innovations in Undergraduate Physics
SoC	Stages of Concerns
SoCQ	Stages of Concern Questionnaire
SCALE-UP	Student-Centered Active Learning Environment for Undergraduate Programs
TFA	Teach for America
TQE	Teacher Quality Enhancement

1 THE PROBLEM

Purpose of the Study

The purpose of this study is to investigate from a physics professor's perspective how teaching for conceptual change is conceptualized and practiced by a physics professor during and beyond an extended collaboration with a science education professor focused on teaching for conceptual change. Related questions to this study are (a) what is the evidence of change in a physics professor's *conceptions* of teaching for conceptual change, (b) what is the evidence of change in a physics professor's *practices* of teaching for conceptual change, and (c) what are the learning environment characteristics identified by the physics professor that either facilitated or hindered changes in his conceptions and/or practices in teaching for conceptual change.

Introduction

Education in science, technology, engineering, and math (STEM) has been identified as key factors for both our country's future economic security and national defense and building the skills needed to address the challenges of the 21st century (Glenn, 2000; National Research Council (NRC), 2012b; President's Council of Advisors on Science and Technology (PCAST), 2012). The overarching goals of NRC's (2012a) new framework for science standards for K-12 education is for students to have the skills to enter careers in science, engineering, and technology, along with being scientifically literate, with the ability to continuously learn in an increasingly complex global society. Physics knowledge plays an essential role in this science literacy required of future citizens to make informed decisions, and positively contribute to society (NRC, 1995). As importantly, high school physics is a gateway course to college and STEM majors (Hoffer, 1995; W. Tyson, Lee, Borman, & Hanson, 2007). It exerts a major influence on the retention of students in STEM majors, a key factor in minorities pursuing STEM majors (W. Tyson et al., 2007), and exerts a strong influence in the success of students pursuing advanced degrees in physics (White, 2011).

The American Institute of Physics (AIP) reports from its Nationwide Survey of High School Physics Teachers that the number of seniors having completed high school physics grew from 624,000 (20%) in 1987 to 1.3 million (37%) in 2009. The number of students taking more advanced physics, such as Advanced Placement (AP), International Baccalaureate (IB) or a second year physics course, increased from 4% in 1987 to 13% in 2009 (White, 2011). However, this has not translated to an increase in physics majors. Currently, the total number of US physics graduates remains at the same level as the late 1960s despite the rise in overall college graduates in the ensuing decades (Hodapp, 2011). While large numbers of students are exposed to introductory physics as undergraduates, few chose to take additional courses in physics and even fewer to major in it. For example, The Strategic Programs for Innovations in Undergraduate Physics (SPIN-UP) Project report, published by the National Task Force on Undergraduate Physics, points out that while 350,000 students enroll in introductory physics in US colleges only 3% take another physics course in their college studies (Hilborn, Howes, & Krane, 2003, p. 2).

The improvement of physics education within both secondary and undergraduate education has emerged as a paramount challenge to policy makers and reformers as they look to the future of science education (Singer & Smith, 2013). Research shows the traditional learning environment and structure of introductory physics classes are largely ineffective and need reforming (Singer, Nielsen, & Schweingruber, 2012; Tobias, 1990). Traditionally, introductory physics classes are taught through the format of a large lecture, smaller recitation, and a separate laboratory (Redish & Steinberg, 1999; Wilson, 1994). The instruction is based primarily on the instructor's view of the subject and perception of the student (McDermott, 1993). Research indicates students enter these classes with pre-existing notions, based on personal beliefs and intuition about the physical phenomena to be studied, that are inconsistent with current scientific understanding. Teacher-centered lectures provide little change in the students' conceptions of these phenomena (Hake, 1998; Halloun & Hestenes, 1985).

Many of these challenges stem from the learning environments of the classroom, physics community, and the culture of the university. Teachers teach as they were taught unless impacted by a transformative experience. At the core these attitudes often belie the differences between expert and novice views of learning. Physicists, as physics instructors, often exhibit novice views of learning that do not distinguish between how their students approach and solve problems and how they as an expert do. Furthermore, novice views of learning fail to embrace the more modern constructivist view of learning that students construct their knowledge through active learning in social environments (Singer et al., 2012). Research indicates students' prior conceptions often conflict with scientific ideas and are robust in resisting change (Hammer, 1996). Research theories, such as the conceptual change model (Posner, Strike, Hewson, & Gertzog, 1982), have emerged as frameworks for instructional design, based on a more expert view of learning that emphasizes identifying and addressing students' preconceptions. Often the novice views of learning foster a strong inertia within physics departments against embracing or even trying reformed teaching methods (Redish & Steinberg, 1999) .

Change models often target teachers' attitudes and beliefs, holding that if these are changed their practices will change, resulting in a change in students' learning (Guskey, 1986). Yet, change involving a transformation in a teacher's beliefs requires a conceptual change in a teacher's preconceptions of teaching and how to teach science. These conceptions have been shown to be resistant to change even with direct instruction targeting them. Teacher's change involves interactions at the organizational, classroom, and individual domains. Within the change process, all of these domains are embedded, interrelated to each other, and influencers. Therefore, an effective model of change must be able to represent all of these domains and the interactions between them.

Professional development is the most common change stimulus within the teaching profession both in higher learning and K-12 education. Professional development, which targets university science faculty teaching, has been found to be beneficial to student learning (D. W. Sunal, Sunal, Turner, & Steele, 2012). Current reforms emphasize professional development involving collaboration between College of Arts and Sciences and College of Education (PhysTEC, 2013; Singer et al., 2012). Common practices include co-teaching, course redesign, and peer consultation. However, rigorous research studies on the change produced by these types of collaborative professional development on science faculty members' conceptions and practices in teaching and learning are lacking.

Rationale for the Study

The need for effective teaching by university physics faculty is great. Collaboration between science departments and educational colleges has been identified as a key factor in improving undergraduate science and science teacher training programs (Coffin, 2002; Etkina, 2005; Kaplan & Edelfelt, 1996). The learning environments within physics departments remain largely characterized by teacher-centered classrooms, faculty with more novice views of learning, and a low priority placed on teaching methods (D. K. Cohen, 1988; Ebert-May et al., 2011; Postareff, Lindblom-Ylanne, & Nevgi, 2008; D. W. Sunal et al., 2001). In this environment our STEM students, future teachers, and science professors are trained. As research shows, teachers most often teach as they were taught producing a self-perpetuating process of poor science teachers with preconceptions of teaching which do not reflect what research shows as the most effective (Darling-Hammond, Wise, & Klein, 1995; Trigwell, Prosser, & Waterhouse, 1999; van den Berg, Locaylocay, & Gallos, 2006). This dilemma has reformers calling for physics departments to change how they teach by collaborating with education departments (Bouwma-Gearhart, 2012; Etkina, 2005; Hilborn et al., 2003). The research shows prior conceptions are robust and reluctant to change, making this a very difficult and complex process (Hammer, 1996; Wandersee, Mintzes, & Novak, 1994). The missing piece is research on the teacher-change process in physics faculty members as a result of collaborating with education departments. This gap is the context for the study: a case study of the change process of a physics professor's conceptions and practices of teaching and learning during a collaboration with a science education faculty member.

Personal Background

As a currently practicing high school physics teacher, I find the shortage of highly qualified physics teachers as more than just an abstract problem. Like a large percentage of physics teachers, my academic background was not physics. Engineering was both my chosen major and initial profession prior to my entrance into the teaching profession. My gateway into the classroom was through the alternative path of Teach for America (TFA). After a six-week intensive summer training program, combining pedagogy and student teaching, I began teaching middle school life science. During my second year of teaching, I enrolled in a teacher training program at a local university to secure my teaching certification in broad-field science. The program required only educational classes without any additional science content courses. Passing the required state examination in both general science and physics, I secured teaching certifications in both. Immediately, I was employed as a physics teacher in a large high school, teaching all levels of physics from general to advanced placement (AP) and International Baccalaureate (IB). The first few years I traveled a steep learning curve. While my engineering background provided an adequate general content knowledge in physics, my engineering knowledge was specialized leaving gaps in several key areas of physics. Even more challenging was my lack of effective physics pedagogy. Utilizing more experienced teachers' advice and lesson materials, trial and error in my classroom, and self-initiated summer enrichment, I slowly progressed into a more competent physics teacher. Looking back, I realize almost all of this progress was self-initiated with limited formal mentorship or professional development.

Now with over a decade of experience as a physics teacher, I am acutely aware of the scarcity of experienced physics teachers. None of my fellow physics teachers at my high school (3000+ students) were physics majors. There was a strong reluctance among these teachers to teach the more advanced physics classes (AP and IB physics), due largely to feeling ill-prepared. As our student numbers grew in these advanced physics courses, in similar fashion to the national trend, I struggled alone to meet this need while my colleagues concentrated on general physics. Former teachers, who taught advanced physics in my school, left for a number of reasons, but a major factor was the workload created by large classes of advanced physics students. (During this study, I have joined them in leaving to continue teaching physics at a private, international high school.) The administration actively sought other experienced physics teachers, but struggled each year to find them. Instead, they hired inexperienced teachers with math and other science backgrounds. When I have shared my background with other educational professionals, the immediate comments seem to be about how rare this is and how fortunate my school is to have a physics teacher with my background. Having experienced this firsthand and not wanting to continue to be part of an endangered species of teachers, I am motivated in finding better paths to producing competent physics teachers with a good grasp of both the content knowledge and pedagogical knowledge.

"Traditional" best describes the majority of my past teaching. Following in the pattern of how I learned physics, the major component was lecture, followed by recitation sessions with model problem solving, plus students' labs dominated by highly structured verification-like labs. My underlying belief was what worked for me, would also work for my students. My focus was on being a dynamic lecturer, utilizing both demonstrations and relevant applications to better transmit my knowledge to my students – all characteristics of a novice understanding of teaching and learning. Through my studies toward a doctorate in science education, my eyes have been opened to the importance of addressing students' preconceptions and of facilitating more active learning experiences. Now five years later into this transformation of shifting from a teacher-centered approach to a student-centered approach, I am experiencing positive learning results, indicated by international standardized test results and student feedback. My students are encouraged to express their ideas through facilitated scientific discourse and guided inquiry. The positive results have reshaped my views to a more constructionist view of learning. In the midst of experiencing my own conceptual change in my approach to teaching, I desire to understand this change process more deeply.

Reflecting on all of this in my role as a researcher, involved in a study of the effectiveness of a course for perspective science teachers combining physics content with conceptual change pedagogy, questions arose on how this experience was changing the physics professor's teaching conceptions. I began to ask, How can conceptual change in teaching and learning develop in a science university faculty member? What are the major influences in such a change? Is it linked like mine to close collaboration with science educators who have more developed expert views of teaching and learning? These questions, stemming from my own personal experience, lie at the heart of my motivation in conducting this research. My goal in this research was to foster not only my own personal change, but to help inform and improve the field of physics education field. My objective was to ultimately help produce more and better expert physics teachers, who can nurture the widespread physics understanding our students need to be informed and influential citizens of the world..

2 REVIEW OF THE LITERATURE

Literature Review

Experts predict the United States faces a large future shortage in its scientifically trained workforce and science teachers (Glenn, 2000; PCAST, 2012). This future deficit is especially severe in physics where the graduation of physics majors and physics teachers continues to lag, despite ever increasing numbers of college graduates. Compounding this problem is the inextricable link between the shortage of physics majors to the shortage of highly qualified secondary physics teachers (Hodapp, 2011). This shortage of physics teachers is deeply troubling as research has shown that the success of reforming K-12 science education to adequately prepare students for the 21st century workforce depends on the preparation of science teachers (Bybee & Fuchs, 2006; Etkina, 2005; Glenn, 2000). Introductory physics courses with a tradition of being ”weed out” courses, variations of courses designed for prospective physicists, and traditionally large teacher-centered lecture courses are strong deterrents to potential physics majors and teachers (Redish & Steinberg, 1999; Tobias, 1990; Wilson, 1994).

While there is a strong tradition in Physics Education Research (PER) of introducing reformed teaching methods centered on active learning within introductory physics with related research showing the effectiveness of these methods, the traditional learning environment still prevails (Handelsman et al., 2004; Henderson & Dancy, 2007; Redish, 2003). Teachers teach as they were taught, not as they are told to teach. To initiate change in teachers' beliefs and practices, teachers must experience a powerful stimulus, often one that involves active learning in a collaborative setting for a significant duration (Darling-Hammond et al., 1995; Desimone, 2009; van den Berg et al., 2006).

This literature review begins with teachers' conceptions of teaching and learning, followed by the process of conceptual change positioned within the larger context of pedagogical concept knowledge (PCK). Next, the learning environments in which change within science faculty takes place are considered. Finally, the potential stimulus for change of collaboration between physics faculty and science education faculty is examined within the broader framework of professional development (PD) specifically targeting co-teaching. The emphasis throughout is the context of the conceptual change process as experienced by a physics professor within a traditional physics department. The looming challenge of a physics teachers' shortage requires change in undergraduate physics classrooms to attract and retain future teachers; classroom changes predicated on teacher change will be discussed.

Conceptions of Teaching and Learning

In general, a conception "is taken fundamentally to concern the experienced meaning of one specific part of the surrounding world" (Svensson, 1989, p. 531). Conceptions refer to individuals' meaning and understanding of phenomena (Pratt, 1992; Strike & Posner, 1992; Svensson, 1997). Individuals construct abstract concepts from sets of experiences which are only partially shared with others (Entwistle, 1997). These conceptions are dependent on both the individual's activity and the reality of the world external to the individual. The phenomenon of focus in this study is teaching and learning.

Teachers' conceptions of teaching influence their approaches to teaching which influence students' approaches to learning and ultimately influence students' learning outcomes (Kember, 2009; Kember & Kwan, 2000; Trigwell et al., 1999). This impact of conceptions of teaching on teaching and learning can be seen in a model (Figure 1) by Kember (2009).

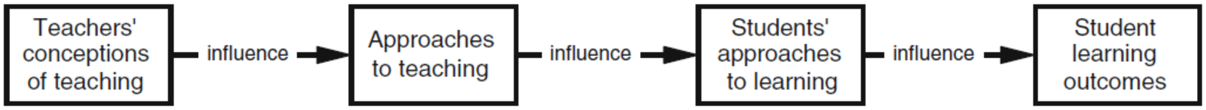


Figure 1. Impact of Conceptions of Teaching on Teaching and Learning. Adapted from "Promoting Student-centered Forms of Learning Across an Entire University," by D. Kember, 2009, *Higher Education, 58,* p. 2. Copyright 2009 by Springer Science & Business Media B.V.

Teaching beliefs of university faculty are consistently directed into the two broad orientations of teacher-centered/content-oriented and student centered/learning-oriented (Biggs & Tang, 2011; Kember, 1997; Kember & Kwan, 2002; Pratt, 1992; Prosser, Trigwell, & Taylor, 1994; Vermunt & Verloop, 1999). In teacher-centered instruction, the student is often viewed as a 'blank slate' on which an expert bestows knowledge focusing on facts, skills, and general knowledge. In student-centered instruction, the students construct their own knowledge which the teacher facilitates by focusing on learning processes and strategies, assisting the students in constructing their knowledge (Cuban, 1990; Kember, 1997). Additional studies have further synthesized these categories. Kember (1997) proposed five conceptual categories of teaching

- Imparting information
- Transmitting structured knowledge
- Student-teacher interaction/apprenticeship;
- Facilitating understanding
- Conceptual change/intellectual development

The first two categories represent a teacher-centered approach to teaching and the last categories represent a student-center approach. The student-teacher interaction represents a transitional conception which Kember described as an intermediate position.

Similarly, Biggs and Tang (2011) identified three common levels of thinking about teaching determined by the focus of the teaching: what students are, what teachers do, and what the student does. Biggs and Tang propose that these levels represent a sequence of development in teachers' thinking and practice. As the last level, "what the student does" indicates, learning is tied with activities, not just teaching. The teachers' role is to align their teaching practices with students' learning practices and help the students engage in activities appropriate to the quality of learning desired. Within these levels are seen an increasing level of complexity from the less sophisticated teacher-centered approach to the more sophisticated student-centered approach (Akerlind, 2008; Trigwell et al., 1999).

Five empirical interview-based studies on a phenomenographic methodology have focused on university teachers' conceptions or approaches to learning. Each study produced a hierarchical set of interrelated categories characterizing the different ways teaching can be conceptualized (Akerlind, 2004; Dall'Alba, 1991; Martin & Balla, 1991; McKenzie, 2003; Prosser et al., 1994). These five studies are similar to the aim and methodology of my research study. Table 1 compares the conceptual categories between each study (McKenzie, 2003).

(1) Dall'Alba (1991) interviewed 20 teachers from various fields at Australian universities. She proposed seven categories of teaching conceptions of teachers. Dall'Alba's categories proceeded from less sophisticated to more sophisticated in a hierarchical pattern. Higher categories included an awareness of the ideas of the previous lower categories, but not vice versa.

(2) Martin and Balla (1991) interviewed 13 teachers enrolled in a course on higher education. They proposed seven categories hierarchically arranged, grouped into three levels: presenting information, encouraging active learning, and relating teaching to learning. The seven categories showed the shift of focus within these levels.

(3) Prosser, Trigwell, and Taylor (1994) interviewed 24 teachers in chemistry and physics departments at two Australian Universities. They identified six hierarchical categories within the teachers' conceptions toward teaching. Prosser et al. further identified seven categories of teachers' approaches to teaching. These approaches were:

A. A teacher-focused strategy with the intention of transmitting information to the students;
B. A teacher-focused strategy with the intention that students acquire the concepts of the discipline;
C. A teacher/student interaction strategy with the intention that students acquire the concepts of the discipline;
D. A student-focused strategy aimed at students developing their conceptions;
E. A student-focused strategy aimed at students changing their conceptions. (Prosser & Trigwell, 1999)

Trigwell and Prosser (1996) found a close relationship between the teachers' conception of teaching and their approach to teaching. Teachers who adopted a more student-focused approach in their teaching exhibited a more complete conception of teaching. A teacher's conceptions were proposed as limiting to a teacher's approach.

(4) McKenzie (2003) interviewed 27 university teachers in a longitudinal study consisting of 3 interviews over 2 years. Her focus was how teachers' conception of teaching change. She identified six, hierarchical categories arranged in order of increasing complexity. Each category was divided into a structural and referential aspect. The structural aspect included the focus of the teaching, ranging from teaching and content to student change. The referential

aspect described the method of teaching, ranging from transmitting to challenging, thus enabling students to change.

An additional focus of McKenzie's study was teacher change. She identified four major categories of change (cA-cD) with the first having two sub categories (cA1 & cA2). These change categories were:

> cA: Change in teaching as changing the content which is taught in order to improve teaching;
>
> cA1: Changing the selection of content included or excluded in order to improve teacher interest or student motivation;
>
> cA2: Changing the way the content is organized for and represented in teaching in order to improve teaching efficiency or teacher comfort;
>
> cB: Change in teaching as changing teaching strategies in order to improve teaching;
>
> cC: Change in teaching as relating teaching more closely to learning in order to improve students' learning;
>
> cD: Change in teaching as coming to experience teaching in a more student-focused way through improving understanding of teaching and students' learning. (McKenzie, 2003)

These categories closely relate to McKenzie's categories of teaching description and fall into three overall teaching-focused groups: teaching focused (cA1, cA2, cB), student learning focused (cC) and teaching understanding and student learning focused (cD) similar in structure to the three categories of Kember (1997). Described as a "semi-inclusive hierarchy", the change categories were all linked in a hierarchical structure except for categories cA and cB, identified in parallel instead of inclusive. The change category delineated the structure of the experienced change and the teaching aspect of variation which facilitated the change.

Table 1

Summary of Phenomenographic Research Studies on Conceptions of Teaching.

Sophistication Level		Dall'Alba, 1991	Martin and Balla, 1991	Prosser, Trigwell and Taylor, 1994	McKenzie, 2003	Akerlind, 2004
Complex conceptions		G. Bringing about conceptual change	3. Relating teaching to learning	F. Helping students change conceptions	F. Teaching as challenging and enabling students to change the relation between themselves and the world	
	Student-focused	F. Exploring ways of understanding from particular perspectives	2. Encouraging active learning: experiential focus vocational variation	E. Helping students develop conceptions	E. Teaching as guiding students to explore and develop professionally and become independent as learners	Student learning focused
		E. Developing the capacity to be expert			D. Teaching as facilitative process of relating teaching to learning to help students to develop their own disciplinary or professional understanding	Student engagement focused
Intermediate conceptions		D. Developing concepts and their interrelations	2. Encouraging active learning: discussion focus	Helping students acquire: D. teacher's knowledge C. concepts of the syllabus		
	Teacher-focused	C. Illustrating the application of theory to practice	2. Encouraging active learning: motivational focus		C. Teaching as teacher-focused interaction with students and student activity to help students to become capable of using the concepts and methods of the discipline or profession	Teacher-student relations focused
		B. Transmitting information	1. Presenting information: content organization focus	B. Transmitting teachers' knowledge	B. Teaching as organizing, explaining, and demonstrating information so that students acquire disciplinary concepts and methods	
Limited conceptions		A. Imparting information	1. Presenting information: delivery focus	A. Transmitting concepts of the syllabus	A. Teaching as transmitting information so that it is passed on to students	Teacher transmission focused

Adopted from McKenzie (2003).

Four patterns of how teachers changed in relationship to their experience of teaching were identified showing an "inter-related connection" between the teaching change experienced and whether the view of teaching remained teacher-focused, evolved, or remained student-focused. The pathways of change related to expansion of teacher's awareness of ways of experiencing teaching, but did not necessarily lead to expansions in how they taught (McKenzie, 2003).

(5) Akerlind (2004) interviewed 28 university teachers on what being a teacher meant to them. She presented four hierarchical conceptual categories on understanding about being a university teacher. Unique to her study was the identifying of three aspects to teacher gain: new content knowledge, teaching enjoyment, and understanding. These gains were hierarchical, adding on to the previous gain as the conception of teaching grew in sophistication. Only the last category (student-learning focused experience) comprised all three types of gain.

Comparing each of these studies (Table 1), a similar hierarchical was evident with the lowest level teacher focused on disseminating information and the highest level on student-focused. Differences existed in the more complex levels with D'all Alba, Prosser et al., and McKenzie envisioning students changing their conceptions while Martin & Balla and Akerlind focused only on student learning. Dall'Alba and Prosser et al. specifically associated the most sophisticated conception of teaching with conceptual change. Similar progressions from teacher-centered to student-centered were seen in each structure. The similarities between the studies supported the phenomenographic position that there are a finite number of ways to experience a phenomena (Marton, 1994). Other non-phenomenography studies have produced similar categories of teachers' conceptions (Kember & Kwan, 2000; Samuelowicz & Bain, 1992, 2001), further supporting this.

How are teachers' conceptions of teaching formed? Lortie (1975), in his landmark study based on interviews with 94 schoolteachers, characterized teaching as a flat career. Entrance into teaching was marked by the thrusting of a teacher mainly alone into a classroom underprepared, following unremarkable college training. This initial shock of the classroom often caused teachers to fall back on their experience as students. Classifying this period of over 13,000 hours in K-12 education as 'the apprenticeship of observation,' Lortie found this as the main shaper of teachers' views about teaching. As Stigler and Hiebert (1999) pointed out, "Teaching…is a cultural activity…Teaching, like other cultural activities, is learned through informal participation over long periods of time. It is something one learns to do more by growing up in a culture than by studying it formally" (p. 86). In this local culture of the classroom, the routine of the activities and their perception become taken for granted and then perceived as reality. It is the local perceptions and interpretations that make classroom practices so difficult to change and are often at the source of the intractability of faculty's views and practices on teaching and learning (Gallimore, 1996). Teachers' classroom learning environments showed consistency over time in how they teach and these "habitual patterns" of teaching were linked with teachers' theories about teaching (Gow & Kember, 1993; Trigwell et al., 1999; Vermunt & Verloop, 1999). Next, the specific knowledge associated with teaching both in conception and practice is briefly discussed to provide a framework in which teacher change occurs.

Pedagogical Content Knowledge

Achieving excellence in teaching is complex and difficult. It requires a combination of both content expertise and methodological technique with an understanding of how students learn (Andrews, Garrison, & Magnusson, 1996). This specialized knowledge of teachers, consisting of deep content knowledge of their subject, an understanding of how their students learn, and the interlinking of both of these, form what is known as their pedagogical content knowledge (PCK). Shulman (1987) coined the term PCK and described it as "the blending of content and pedagogy into an understanding of how particular topics, problems, or issues are organized, represented, and adapted to the diverse interests and abilities of learners, and presented for instruction" (p. 8). While the idea of PCK has greatly expanded since its inception, the key elements of PCK consistent through the literature are knowledge of representation of subject matter and understanding of specific learning difficulties and student conceptions (Ball, Thames, & Phelps, 2008; van Driel, Verloop, & de Vos, 1998). Magnusson, Krajcik, and Borko (1999) identified five aspects of PCK that can be developed in a science teacher: science curriculum, students' understandings of specific science topics, assessment, instructional strategies for teaching science, and orientations toward science teaching. Students' understandings of specific science topics and instructional strategies for teaching science represent areas that lie outside the knowledge expertise of a general physics faculty member and involve a significant change process to develop (Magnusson et al., 1999; NRC, 1996). Change within these two aspects is now examined concentrating on conceptual change and teaching for conceptual change.

Knowledge of students' understanding of science.

To be a knowledgeable teacher on how students' understand specific science topics requires a familiarity with both the prerequisite knowledge and various approaches students use for learning particular concepts. Areas of difficulty include the abstract nature of science concepts, difficulty in problem solving, and conflict between the science concept and the students' prior knowledge. One of the most challenging areas, as well as one of the most studied, is the conflict of students' prior knowledge with science knowledge. Historically, a plethora of terms have been used in the literature to identify students' prior knowledge which conflict with scientifically-accepted knowledge. Examples include common naïve conceptions, preconceptions, intuitive physics, alternative conceptions, alternative frameworks, commonsense ideas, and everyday conceptions. These are generally referred to as misconceptions (Gunstone & Northfield, 1986; Guzzetti, Snyder, Glass, & Gamas, 1993). However, misconceptions connote that the ideas are wrong and must be replaced, something not supported in more recent conceptual change literature (Hammer, 1996; Maskiewicz & Lineback, 2013; J. Smith, diSessa, & Roschelle, 1993). In this paper, these are termed "students' preconceptions". Conceptual change is the research area that encompasses both the knowledge about students' preconceptions and the change process focused on helping to align preconceptions with accepted scientific conceptions.

A brief overview of conceptual change is provided as an example of part of the specific knowledge a physics faculty member would need to develop in his or her PCK.

Conceptual change theory.

One of the most important developments in the last three decades of science education research is the domain of students' conceptions or preconceptions ideas (David E. Brown & Hammer, 2008; Treagust & Duit, 2008; Viennot, 2008; Wandersee et al., 1994). It is now commonly accepted that students enter science classrooms with a set of common sense beliefs and intuitions about how the world works, based on their personal experiences. These "preconceptions" have been found in many cases to be resistant to change even after significant instruction (David E Brown, 2014; Treagust & Duit, 2008). The initial focus of researchers on students' conceptions was identifying students' preconceptions in specific content areas within Physics Education Research (PER), where traditional physics instruction often failed to develop students' conceptual physics understanding (Hake, 1998; Halloun & Hestenes, 1985; McDermott, 1991). Thus, students' lingering preconceptions were researched and identified, followed by the development of specific teaching strategies and curriculum to address them (McDermott, Schaffer, & Somers, 1993; Pride, Vokos, & McDermott, 1998). Hammer (1996) summarized the general view of "preconceptions" in the science education community as "*conceptions* that

1. are strongly held, stable cognitive structures;
2. differ from expert conceptions;
3. affect in a fundamental sense how students understand natural phenomena and scientific explanations; and
4. must be overcome, avoided, or eliminated for students to achieve expert understanding" (p. 99).

Evolving from this research on students' conceptions was conceptual change theory. Conceptual change theory is rooted in constructivism, a theoretical framework, which proposes that knowledge is constructed through interactions between the learner and his or her world, developed and communicated within a social context (Crotty, 1998). Constructivism is characterized by viewing knowledge as a constructed process, involving actively generating and testing alternative propositions (L. M. Tyson, Venville, Harrison, & Treagust, 1997). As a result, theories of conceptual change models have emerged as frameworks for instructional design.

The foundational article for conceptual change was by Posner, Strike, Hewson, and Gertzog (1982). Posner et al. identified two types of conceptual change: assimilation and accommodation. In assimilation, "students use existing concepts to deal with new phenomena" (p.211). When students' concepts are inadequate to deal with new phenomena, then a more radical form of conceptual change is required – accommodation. Drawing on Kuhn's (1970) changing paradigms that occur in scientific revolutions, they identified an analogous process in learning where students must change their ideas when they are inadequate to explain a new phenomenon. For accommodation to occur four conditions must be met: dissatisfaction, intelligibility, plausibility, and fruitfulness (Posner et al., 1982).

Hewson (1981) defined the extent to which a conception meets the three conditions of "intelligibility, plausibility, and fruitfulness" as the "status" of a person's conception. The fourth condition of dissatisfaction is directly related to status. Dissatisfaction with a concept leads to a lowering of status. The concept may still be intelligible but no longer fruitful or plausible. This lowering status caused by dissatisfaction leads the learner to consider an alternative conception; the status rises after the original concept's status, which had been blocking the alternative, is lowered. If the alternative conception proves intelligible, plausible, and fruitful the learner replaces his or her previous conception undergoing conceptual change.

Conceptual change is now one of the most influential research traditions within the science education community. As of 2009, over 8,000 research articles have been published on the role of students' and teachers' conceptions in the teaching and learning process (Duit, 2009). Expanding from the Posner et al.'s model, a variety of theoretical lens have been proposed as frameworks for explaining conceptual change. Broadly, these can be classified as epistemological, ontological, and social/affective. The epistemological lens focuses on how students perceive their own knowledge of the phenomena being studied; the ontological lens looks at how the student perceives the nature of the phenomena being studied; and the social/affective lens examines the social/affective conditions needed for conceptual change to take place (L. M. Tyson et al., 1997). Many of these perspectives have empirical evidence supporting their frameworks' contribution to conceptual change. This multiplicity of theories and evidence strongly supports the complexity of conceptual change. Many experts now agree that conceptual change is a complex process involving multiple factors that are context dependent and cannot be explained with a single unitary view of conceptions and conceptual change (David E. Brown & Hammer, 2008; diSessa, 2008; Gupta, Hammer, & Redish, 2010; L. M. Tyson et al., 1997).

Knowledge of instructional strategies.

Conceptual change, a very complex process, lies at the heart of understanding students' difficulties in learning science content and is an essential aspect of a teacher's PCK. Linked with conceptual change are teaching methods for facilitating it or teaching for conceptual change. In Magnusson et al.'s (1999) five aspects of PCK, teaching for conceptual change falls under 'knowledge of instructional strategies.' These include both a broad level knowledge of subject-specific strategies and a narrower level knowledge of topic-specific strategies. Teaching for conceptual change involves both of these: a broad general knowledge of strategies that focus on conceptual change and then specific knowledge of specialized strategies for bringing about conceptual change on definite topics.

Teaching for conceptual change.

In a literature review of strategies to promote conceptual change, Scott, Asoko, and Driver (1992) identified two major groupings. The first group focused on conceptual exchange, where cognitive conflict between competing concepts was targeted. Within this, the learner was central. The second group focused on assimilation which seeks to build on a learner's current conceptions. These focus more on the strategies used by teachers to facilitate assimilation, not accommodation. Therefore, teaching for conceptual change requires a shift in the focus in the classroom from what is being taught to what is being learned by the student. For it is the learners that “construct and restructure their schemes of the world, through their own mental activity, as a result of experience with phenomena and social interactions” (Driver & Scott, 1996, p. 95). Prior to facilitating conceptual change, ascertaining the current conceptions and knowledge students possess in the area being taught is critical. The conceptual pathways, that lead students from their nascent conceptions to more developed scientific conceptions, can be sought through specific teaching strategies. These conceptual pathways cannot be discovered prior to teaching as knowledge of them are ascertained only through practice (Scott et al., 1992). Probing into what the student has learned often shows the limitation of their understanding and how difficult conceptual change is to achieve. The conceptual change process may take years as many case studies have shown (Taber, 2001; Thorley & Woods, 1997; Tytler, 1998). Conceptual change is a change in beliefs or as Taber (2001) states, “conceptual development implies a shift in the learner’s epistemological profile, and the job of the science educator becomes that of facilitating such a shift” (pp. 732-733).

Hewson, Beeth, and Thorley (1998) defined “teaching for conceptual change” as “teaching that explicitly aims to help students experience conceptual change learning, and meets guidelines consistent with the conceptual change model” (p. 200). Hewson et al. (1998) proposed guidelines for teaching conceptual change, based on their developmental work and a synthesis of the literature. Their framework described a requirement for (a) students’ and teachers’ ideas to be explicitly considered in the classroom discourse; (b) classroom discourse being explicitly metacognitive; (c) the status of ideas discussed and negotiated; and (d) the justification for ideas and for status decisions being explicit components of the curriculum. The first requirement focused on students' ideas being made explicit, considered in similar ways to teacher's ideas, and were valued enough to become part of the classroom discourse. Students become cognizant of, understand, and possibly adopting ideas they had not considered previously. The second requirement dealt with metacognition, recognizing it was inherent to the process of conceptual change. Metacognition then became an intentional teaching strategy where learners monitor, integrate, and extend their own learning. The third requirement targeted the negotiating of the status of ideas. The focus of activities became raising the status of an idea by making it more intelligible, plausible, and fruitful for the learner (Hewson, 1981). These activities helped present and develop ideas, apply ideas to different contexts, and link these with other ideas. Similarly, activities to lower the status of ideas, such as discrepant events, need to occur often simultaneously. The final requirement was to make the justification behind accepting ideas and status decisions explicit in the classroom. Open discussion was encouraged explicitly sharing both students' choice of ideas and reflecting on their decision process (Beeth & Hewson, 1999; Hewson et al., 1998). Teaching for conceptual change, as referenced in this study, was based on this framework.

Conceptual change in science teachers.

Just as students enter the classroom with preconceptions of science, so teachers also enter the classroom with preconceptions of teaching and how to teach science. Many of the preconceptions of teaching and learning were formed through the "apprenticeship of observation". Similarly to students' preconceptions, these conceptions have been shown to be resistant to change even with direct instruction targeting them. Therefore, conceptual change involves science teachers and educators as well. Hewson (1992), identified four ways conceptual change enters science education – "learning science, teaching science, learning how to teach science, and teaching how to teach science" (p. 10). Of these only one involved students. All the others focused on science teachers and educators. Hewson refined these ideas into what he terms a *conception of teaching science*. This involved teachers' views of knowledge, learning and teaching, content knowledge, their teaching methods, along with context dependent information on content, students, and the school environment (Hewson & Hewson, 1988; Hewson et al., 1999). Teacher conceptual change, with its inclusion of teachers' beliefs and practices on teaching and learning, falls within the broader research field of teacher change. This will be examined in more depth.

Learning Environments

Content is essential to both a teacher's PCK and conceptions of teaching science for these activities occur within a specific setting which influence their appropriateness and effectiveness. This context is generally referred to as the learning environment. Learning environments include the social, psychological, and pedagogical contexts where learning occurs and are determinants of learning, affecting both student achievement and attitudes (Fraser, 1994, 1998). Learning environments occur at multiple levels from the classroom environment, to the school environment, to out-of-school environment (Fraser, 1998). Learning environments are examined starting at the classroom level followed by the departmental level, the professional community level, and the university level. This review emphasizes the typical learning environments in which physics faculty members work, and how learning environments influence epistemological beliefs and practices.

Closely linked with these learning environments is the culture. Culture refers to "the shared knowledge and schemes created and used by a set of people for perceiving, interpreting, expressing and responding to social realities around them" (Lederach, 1995, p. 9). Similar to learning environments, culture occurs at many different levels, all of which influence the learning in the classroom. Bransford, Brown and Cocking (2000) pointed out, "Teaching and learning must be viewed from the perspective of the overall culture of the society and its relationship to the norms of the classrooms" (p. 147). Therefore, culture is an important influencer as well as part of the learning environment (J. S. Brown, Collins, & Duguid, 1989; Demir & Ellett, 2014; Fisher & Waldrip, 1999).

Recently, Demir and Ellett (2014) proposed a working model to illustrate the interconnectedness of different cultural and learning environments (See Figure 2). The different learning environments were shown as expanding circles, beginning with the classroom learning environment and expanding out to broader learning environments, including the school and external learning environments. Each level interacts and influences the others. McDuffie and Graeber (2003), in a study of the influence of the institutional culture of universities on the reform-based practices of math professors, proposed a framework to identify and analyze the norms and practices that influence professors' practice. Their devised framework consisted of a teaching and learning context, the professional community, and the university's reward system. Utilizing this framework, the different learning environments and cultures that affect a physics professor's teaching and learning were examined. The study started with the teaching and learning context of the classroom, addressed the professional community culture, and concluded with the university culture.

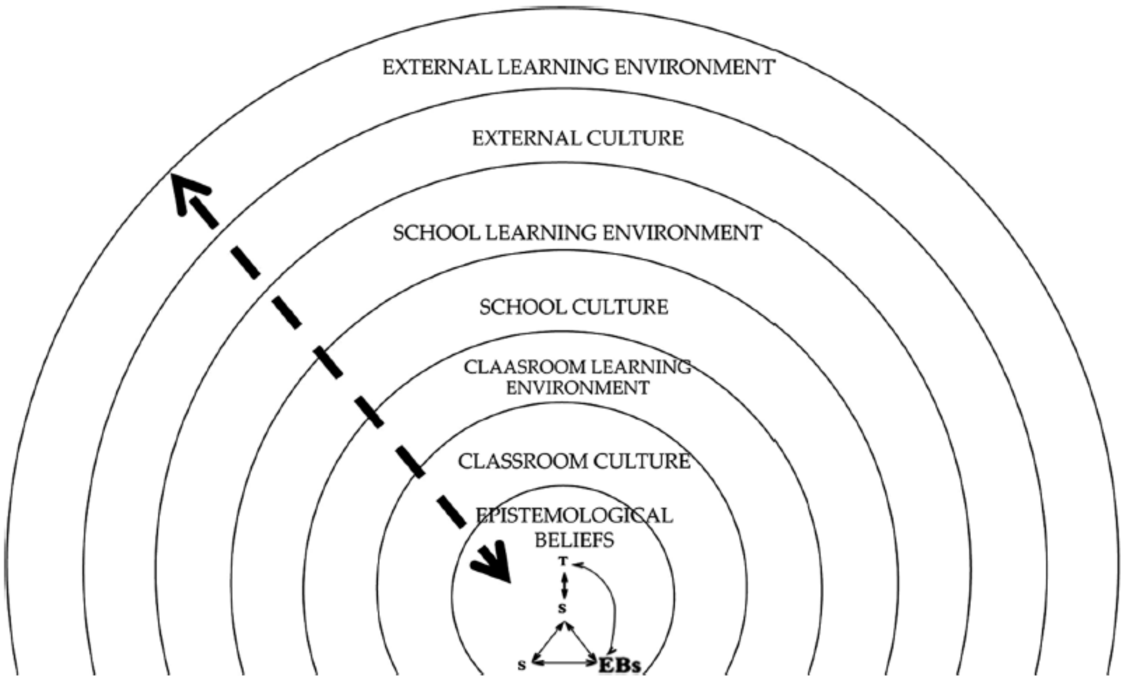


Figure 2. A Working Model Linking the Development and Strengthening of Students' Epistemological Beliefs, Culture, and Learning Environment Characteristics (EBs- Epistemological Beliefs; S- Student; T- Teacher). Adapted from "Cross-cultural Research and Perspectives on Epistemology, Learning Environments, and Culture," by K. Demir and C. Ellett, 2014. In R. Evans, J. Luft, C. Czemiak, and C. Pea (Eds.), *The Role of Science Teachers' Beliefs in International Classrooms from Teacher Actions to Student Learning*, p. 67, The Netherlands: Sense Publishers. Copyright 2014 by Sense Publishers.

Classroom culture.

The culture and learning environment of the college science classroom has seen very little change despite much effort spent in reforming them, dating back well over a century and a half (Cuban, 1990). The prevailing format of college science classes remains teacher-centered instruction utilizing primarily lecture (Ebert-May et al., 2011; Lammers & Murphy, 2002; Thielens, 1987). This contrasts with the more effective student-centered approach utilizing active learning that education researchers and national reformers promote (Duit & Treagust, 2012; NRC, 2012a). The teachers' role is to align their teaching practices with students' learning practices and help the student engage in learning activities appropriate to the quality of learning desired. The learning portrayed in this teacher's regulation of learning practices is "developing a way of thinking and acting that is characteristic of an expert community" (Vermunt & Verloop, 1999, p. 264).

Expert vs. novice knowledge in the classroom.

Expertise is built through the acquisition of propositional and procedural knowledge that is highly organized and used efficiently for solving problems (Billett, 1996; Mestre, 2001). Bransford et al. (2000) in a National Research Council's report highlighted six principles of experts' knowledge and their connections with teaching and learning. Summarizing these: experts' knowledge exhibit meaningful patterns of information; experts' knowledge is organized hierarchically around core conceptions that guide their thinking; experts' knowledge is conditionalized with an understanding of the contexts in which it is relevant; experts have a fluent retrieval of their knowledge; experts' knowledge does not guarantee the ability to teach others; and experts show varying amount of adaptability in the application of their knowledge. Contrasting novices' knowledge, novices often have not developed the conditional understanding of their knowledge through experience in a specific domain of knowledge, have no access to the particular social practice in that field, nor exposure with what that practice prioritizes (Billett, 1996). For example in physics, physicists in solving problems typically emphasize qualitative over quantitative understanding, use multiple representations techniques, and rely on a hierarchical knowledge structure to cue additional knowledge. Novices will categorize based on apparent features of the immediate problem and focus immediately on the quantitative parts of the solution or the equations they will use (Chasteen & Pollock, 2012; Chi, Feltovich, & Glaser, 1981; Mestre, 2001; Van Heuvelen, 1991). Typically, it requires ten years of practice within a field to acquire expertise (Ericsson, Krampe, & Tesch-Römer, 1993). In physics that practice primarily occurs in the classroom and laboratory.

Physics professors, though experts in their field, often have novice views of learning. The physics instructors many not distinguish between how their students approach and solve problems and how they as an expert do. The expert's methods used in problem solving are treated as tacit knowledge that are never explicitly explained to their students, but expected of their students. In contrast, studies showed that students gain significant expertise fairly rapidly through effective instruction, something not always present in physics classrooms (Chasteen & Pollock, 2012; Dufresne, Gerace, Hardiman, & Mestre, 1992; Ericsson, 1996; Schraw, Crippen, & Hartley, 2006). Expert views of learning embrace more constructivist views of learning. These views promote that students construct their knowledge through active learning in social environments which research shows as most effective in student learning (C. W. Anderson, 2007; Mestre, 2001; Redish, 2003).

Epistemological beliefs in the classroom.

Physic professors' novice views on learning and their failure to impart their expert knowledge of problem solving to their students illustrate a link between teachers' epistemological beliefs and practice. Epistemological beliefs are personal beliefs about the nature of knowledge and learning (Schommer, 1994), and their role in the classroom is illustrated by the central role they occupy in Demir and Ellet's (2014) working model (Figure 2). Research in K-12 education has established an understanding of the central role teachers' beliefs play in teachers' practices (Kagan, 1992; Pajares, 1992). A more limited body of research supports a similar link between university teachers' beliefs and their teaching practice (Kember & Kwan, 2002; Quinlan, 1999; Ramsden, Prosser, Trigwell, & Martin, 2007; Samuelowicz & Bain, 2001;

Trigwell, Prosser, & Taylor, 1994). Subsequent research (Ho, Watkins, & Kelly, 2001; Trigwell et al., 1999) linked teachers' approaches to teaching and students' approaches to learning. Teachers who adopt "conceptual change/student focused" were more likely to have students who reported adopting more sophisticated approaches to learning than teachers using "information transfer/teacher focused approaches" (Trigwell et al., 1999). While the limited research provided evidence for a potential link between teachers' conceptions and their practices, there is a need for more rigorous studies that confirm this connection between teachers' conceptions and practices through direct observation of the teachers' practices (Kane, Sandretto, & Heath, 2002).

The development of both students' and future teachers' epistemological beliefs are tied to the learning environment and formal school experience. Thus, it is imperative that the learning environment model conceptions of learning and learning activities that are consistent with the experts' epistemological views of learning.

Departmental culture.

In science departments, the general learning environment is a teacher-centered lecture and recitation model which has changed little over time (D. K. Cohen, 1988; Ebert-May et al., 2011; Postareff et al., 2008; D. W. Sunal et al., 2001). This environment discourages the risk taking, uncertainty, and inquiry needed to transform the general learning environment (D. K. Cohen, 1988; McDuffie & Graeber, 2003; D. W. Sunal et al., 2001). Research has identified knowing and learning as communal acts, dependent on community (P. J. Palmer, 1993). Yet, collaboration in teaching is often at odds with the prevailing departmental culture. Many professors consider teaching, "an intimate exchange between faculty member and student" (Bergquist & Pawlak, 2008, p. 31). Observations by other faculty members are often seen as offensive and disruptive to this practice. Consequently, the study and improvement of teaching by peers arouse ambivalence or even hostility among certain faculty members (Bergquist & Pawlak, 2008; D. K. Cohen, 1988). Collaborating through team teaching, course development, and other collaborative activities (e.g., collaborative teams, learning communities, and other communal scholarship) are often not recognized or rewarded by the department. Common departmental barriers include faculty workloads, limited release time, lack of funds, and obstacles between other departments. These barriers often stymie collaborative teaching initiatives that create a better learning environment for faculty and students (Fairweather, 2008; O'Meara & Braskamp, 2005). More collaborative approaches to leadership of teaching were found to be associated with more conceptual change-oriented and student-focused approaches to teaching (Martin, Trigwell, Prosser, & Ramsden, 2003; Ramsden et al., 2007).

Another strong influence in the attitudes toward teaching at the departmental level was the belief that specialized study is the best preparation for teaching. Professors often reward accomplished students with graduate research assistantship and require less stellar students to fill roles as teaching assistants (Boyer, 1991). In fact, Eble (1972) stated in his book *Professors as Teachers*, “[The professor's] narrowness of vision, the disdain for education, the reluctance to function as a teacher are ills attributable in large part to graduate training” (p. 180). Often the only teaching experience a science faculty member has prior to teaching classes was gained in graduate school. Professional training in teaching at the college level is rare and few universities provide new professors any formal training in teaching (Austin, 2002, 2003; D. W. Sunal et al., 2001). The preparation of professors through specialized study, while less troublesome for advanced graduate studies with small class sizes and students who have adjusted to the graduate school culture, is highly ineffective for introductory science classes with large, diverse populations, where effective instruction requires more general content knowledge and more expert pedagogical methods (Boyer, 1991). As discussed, poorly taught introductory science courses are often implicated in the large attrition of science majors and the reason for few students taking additional science classes (D. W. Sunal et al., 2001; Tobias, 1990). The lasting effect of the science departmental learning environment is captured in this implication, “Science education policy is not made by government; it is made by college science departments” -Shirley Malcolm (as cited in Tobias, 1990, p. 29).

Professional community culture.

Within the physics professional community, the importance of teaching is often acknowledged in the role of a scientist as elegantly stated in a speech by Robert Oppenheimer,

> The specialization of science is an inevitable accompaniment of progress; yet it is full of dangers, and it is cruelly wasteful, since so much that is beautiful and enlightening is cut off from most of the world. Thus it is proper to the role of the scientist that he not merely find the truth and communicate it to his fellows, but that he teach, that he try to bring the most honest and most intelligible account of new knowledge to all who will try to learn (Oppenheimer, 1954)

An asymmetrical and hierarchical relationship can be found between research and teaching. Research carries a higher prestige while teaching is viewed as secondary and derived (Brew, 2006; Schon, 1995). The majority of professors hold that teaching effectiveness, not publications, should be the primary criteria for promotion (Boyer, 1990; Leslie, 2002). Leslie (2002) concluded that there is a ‘disjuncture’ between the intrinsic rewards faculty receive from teaching and the extrinsic rewards aligned with the university’s rewards system for research and publications.

Recently, the physics community has started acknowledging the critical responsibility physics departments carry for undergraduate education. This concern was largely driven by falling numbers of physics degrees and the low retention of students in introductory physics courses within the physics field (Hilborn, 1997). Highlighted by several influential reports (e.g., SPIN-UP Report (Hilborn et al., 2003), Shaping the Future Report (NSF, 1996)) and led by many of the professional physics societies many initiatives and reforms are now underway. Discerning characteristics of these reforms included active collaboration between science departments and schools of education (e.g., team teaching of methods classes for science by both science and education faculty members, the redesign of introductory physics course based on active learning and educational research), and engagement of physics departments with undergraduate physics education (Bouwma-Gearhart, 2012; Hilborn, 1997; Hilborn et al., 2003; McDermott, 2006; Stein, 2001; Wieman, Perkins, & Gilbert, 2010).

A prominent example is Physics Teacher Education Coalitions (PhysTEC) program supported by the National Science Foundation (NSF) and the American Physical Society (APS). PhysTEC (2013) is made up of selected colleges and universities that are developing their physics teacher preparation programs along a national model, which grew out of successful reforms of preparation programs for secondary science and math teachers. Etkina (2005) summarized the key characteristics of a successful physics teacher preparation program as:

1. Future teachers learn physics through the same methods that they should use when teaching.
2. They acquire knowledge of how people learn and how they learn physics.
3. They engage in teaching in environments that mirror the environments that we want them to create later.

4. Future physics teachers master the technology that they can use in the classroom and acquire methods of updating their knowledge and skills.
5. They learn ways to engage their students in actual scientific practices. (p. 4)

The central emphasis is the key role the learning environment plays in preparing future teachers. Something the physics community is beginning to grasp.

University culture.

Strong influences on the physics community, departmental, and classroom cultures stem from the university culture as a whole. Traditionally, the priorities of top universities have been research and production of new knowledge. Yet, the major function of most colleges and universities is to teach (D. K. Cohen, 1988). The priority of research over teaching is apparent in the university rewards system. Tenure and promotion are both weighted toward research and publications at the expense of teaching (W. A. Anderson et al., 2011; Hilborn et al., 2003; NSF, 1996). Studies have shown, on average, the more time faculty members spend in the classroom the lower their average salary (Fairweather, 2005). This is especially true of STEM disciplines, where much of the funding is brought in externally, and strong links remain to the traditional German research university model which valued above all, free scientific research (Bergquist & Pawlak, 2008; Fairweather, 2008).

The university reward system has developed a culture where teaching is not the highest priority of the faculty nor are faculty members known for their interest or accomplishments in teaching (Brownell & Tanner, 2012; Fairweather, 1996; Massy, Wilger, & Colbeck, 1994). Autonomy is another characteristic of the culture propagated by the university reward system. Unlike other professions, there are no examinations or licensing requirements for faculty members (A. M. Cohen, 1998). Tenure and promotion reviews, rarely involve any direct observation of a professor's performance. The code of academic freedom, deeply rooted in autonomy, is linked back to the traditional research university. The practice of academic freedom results in a strong emphasis on independent work and strong individualism (Massy et al., 1994). This carries over to faculty members' teaching as discussed earlier.

Presently, university culture is undergoing change. The following factors are driving changes in higher education: increasing diversity of students' backgrounds, expectations, needs and motivations; heightened emphasis on accountability from the public, businesses and government; fiscal constraint; the accessibility of knowledge in the information age; and more choices and competition in higher education (Austin, 2002, 2003; Boyer, 1990; Fairweather, 1996; Keller, 2001; Levine, 2000). There is a shift from teaching to learning, driven by a growing diversity of students demanding more individualized education. Accompanying this is another shift from teacher-centered to student-centered approaches and new expectations for professors' teaching roles (Austin, 2002; Boyer, 1990; Levine, 2000; Singer et al., 2012). More collaboration between and across institutions is another change. Large scale initiatives related to STEM education, common core curriculum, and PhysTEC involve extensive collaboration between higher education, K-12 education, local, state and national educational leaders. Government and the public sector demand for more accountability from universities, combined with tightening financial resources has been a major facilitator in this (NRC, 2012a; PCAST, 2012; PhysTEC, 2013).

The University System of Georgia's Partnership for Reform in Science and Mathematics (PRISM) initiative highlights this changing picture of collaboration. PRISM was a five year, NSF funded, $34.6 million grant to improve educational achievement levels while closing performance gaps in science and math among Georgia students. The effort involved the collaboration of seven Georgia higher education institutions, 13 K-12 school districts, the Georgia Department of Education, and the Board of Regents of the University System of Georgia. Top strategies of the PRISM initiative were to change the higher education faculty reward system, improve teacher preparation programs in science and mathematics, and have the higher learning institutions provide customized professional learning in science and mathematics for K-12 teachers (Jones, 2008). This illustrates, as noted earlier in Demir and Ellett's (2014) conceptual framework (Figure 2), how different learning environments interact and influence each other. Fundamental change requires a systematic approach of collaboration between the different cultures, influencing each individually and collectively to bring about change.

Professional Development

Reforming and changing the learning environment of science classrooms require collaboration and changing the culture at all levels, but fundamentally it involves changing teachers. The most common approach to facilitating change in teachers is through professional development (PD). Traditionally, PD has been defined as "any activity that is intended partly or primarily to prepare paid staff members for improved performance in present or future roles in the school districts" (Little, 1987, p. 491). For the last thirty years, the most popular forms of PD have remained workshops and courses, but more recently grown to include "embedded professional development", encompassing activities such as co-teaching, mentoring, peer consultation, reflecting on teaching, and action research. (Desimone, 2009; Garet, Porter, Desimone, Birman, & Yoon, 2001; D. W. Sunal et al., 2001; Wei, Darling-Hammond, Andree, Richardson, & Orphanos, 2009; Weimer & Lenze, 1994). A meta-analysis by Loucks-Horsley, Hewson, Love, and Stiles (1998) of PD for math and science teachers identified 15 different professional strategies categorized in five categories: immersion, curriculum, examining practice, collaborative work, and vehicles and mechanisms (Loucks-Horsley & Matsumoto, 1999). Desimone (2009) suggested the critical feature of PD is not its structure but the teachers' learning experience which is often "woefully inadequate" (Borko, 2004; Sykes, 1996). Typically, PD is fragmented without a follow-up or support system, lacks depth, and is inconsistent with what research shows about how we learn (Borko, 2004; Demir, Sutton-Brown, & Czerniak, 2012; Putnam & Borko, 2000). PD is the mechanism most suggested for helping teachers implement education reform, but often the PD itself contradicts the very reform models being championed (Guskey & Huberman, 1995; Little, 1993).

Despite PD's lackluster reputation, research is beginning to show a link between specific characteristics in PD and student learning (Darling-Hammond, 2010; Garet et al., 2001; Kennedy, 1998; Rhoton & McLean, 2008; T. M. Smith et al., 2007). Desimone (2009) found PD that emphasized (1) content focus (e.g., D. K. Cohen & Hill, 2000; Desimone, Porter, Garet, Yoon, & Birman, 2002; Garet et al., 2001; T. M. Smith et al., 2007), (2) active learning (e.g., Borko, 2004; Desimone et al., 2002; Garet et al., 2001; Loucks-Horsley et al., 1998; Loucks-Horsley, Stiles, & Hewson, 1996; Putnam & Borko, 2000), (3) coherence (e.g., Demir, Czerniak, & Hart, 2013; Demir et al., 2012; Garet et al., 2001; D. W. Sunal et al., 2001), (4) duration (e.g., Desimone, 2009; Weiss, Pasley, Smith, Banilower, & Heck, 2003; Yoon, Duncan, Lee, Scarloss, & Shapley, 2007), and (5) collective participation (e.g., Desimone et al., 2002; Loucks-Horsley et al., 1996; Stigler & Hiebert, 1999) positively impacting teachers' learning and practice and promising for improving student performance. While these characteristics of effective PD are generally agreed upon, most K-12 PD falls far short of meeting these criteria (Guskey & Huberman, 1995; Rhoton & McLean, 2008). In higher education, PD is even more limited and isolated (D. W. Sunal et al., 2001).

Higher education PD is now discussed, initially looking at the connection between PD and change in individual teachers' conceptions and practices. Collaborative PD is examined targeting efforts between science and education faculty members focused on improving student learning. The few specific studies found are considered in detail. Then the discussion is broadened to look at similar type of collaborative PD involving science faculty members to understand the current state of science faculty educational collaboration.

Professional development in higher learning.

PD in higher learning reflects many of the practices of K-12 education with the majority of PD being workshops and short seminars, such as orientation or training sessions for new professors, informal and program-based workshops, and brown bag lunches (Rutz, Condon, Iverson, Manduca, & Willett, 2013; D. W. Sunal et al., 2001; Weimer & Lenze, 1994). Other types of PD in higher education institutions include involvement in development processes, such as designing a new class, demonstration lessons, co-teaching, peer coaching, team teaching, mentoring, action research, even to the distribution of literature on effective practice (Demir et al., 2012; D. W. Sunal et al., 2001).

Research into the resulting change in faculty member's practice and student improvement due to PD in higher education was limited regardless of the discipline. It offered limited evidence of its impact on teaching with less evidence of its impact on student learning (Rutz et al., 2013; Weimer & Lenze, 1994).

One exception was Ho, Watkins, and Kelly's (2001) study of a Hong Kong faculty PD initiative aimed at changing teacher's frameworks for conceptualizing teaching and learning through a 12 hour conceptual change workshop over four weeks. The workshop employed four elements to bring about the change: self-awareness, exposure, confrontation, and a commitment building process. Teachers initially reflected on their conceptions of teaching (self-awareness) and were then exposed to alternative conceptions of teaching (exposure). Teachers evaluated their teaching conceptions identifying possible inadequacies (confrontation), examining examples of good teacher (further exposure), and then redesigning their teaching of a topic focusing on their further developed conceptions of teaching (commitment building).

Ho et al.'s (2001) study evaluated the PD's effect on participants' conceptions of teaching, their teaching practices, and their student learning. Three interviews in a pre-, post-, and delayed (1 year later) format provided insight into the effect on participants' conceptions and practices of teaching. Two years of students in a common participant class were surveyed to measure the effect on student learning. The teachers' conceptions were matched to Samuelowicz and Bain's (1992) categories of teaching conceptions (similar to those shown early in Table 1). The study reported 2 of the 12 participants showed enough change in their conceptions of teaching to positively affect their teaching practice. Another four showed noticeable change in their teaching conceptions with possible change in their teaching. The other half showed little to no change. The students' surveys supported this change with the high teacher's group showing significant change in their students, the middle group moderate change, and the low group little change. Ho et al. concluded that a change in a teacher's conception of teaching will likely lead to a prompt change in his or her practice and eventually a change in student learning. These findings support the connection discussed earlier between teachers' conceptions and practices (Trigwell et al., 1999) and demonstrate how developing a more conceptual change framework positively affects teachers' conceptions and practices. Yet, the change is limited.

Within science departments, the majority of PD was aligned with initiatives to bring reform to undergraduate college science teaching with student-focused teaching as characterized in national reform reports (NRC, 1996, 2012a; D. W. Sunal, Wright, & Day, 2004). One approach is to target new professors and their teaching. Initial faculty PD programs impact on teachers' approaches to teaching were found to be limited (Gibbs & Coffey, 2004; Norton, Richardson, Hartley, Newstead, & Mayes, 2005; Postareff, Lindblom-Ylanne, & Nevgi, 2007; Postareff et al., 2008). For example, Henderson (2012) reported on results of an initial teacher training, the Physics and Astronomy New Faculty Workshop, which focused on helping new faculty integrate research-based instructional strategies (RBIS) into their teaching. The workshops successfully informed new faculty about RBIS and motived them to try RBIS in their classrooms. Yet, most participants struggled with successfully implementing these RBIS. Likewise, difficulty in implementation of change initiatives within a classroom is a common finding within the broader field of STEM educational research (Besterfield-Sacre, Cox, Borrego, Beddoes, & Zhu, 2014; Goldsmith, Doerr, & Lewis, 2014; Singer et al., 2012). Building expertise is a difficult process rarely achieved alone in a classroom and often requires expert guidance (as discussed earlier). To this end, collaborative efforts in PD are now considered.

Collaboration in professional development.

Collaboration recognized for its generation of innovations in business and healthcare is now being recommended by policymakers to help bring about innovation and reform in education (Clifford, Millar, Smith, Hora, & DeLima, 2008; Mattessich & Monsey, 1992). Recent policies focused on reforming science teaching have recommended the collaboration between Colleges of Education and Colleges of Arts and Sciences to create more effective teacher preparation programs (Coffin, 2002; Kaplan & Edelfelt, 1996). Initiatives, such as the National Science Foundation's Math and Science Partnership Program and the U. S. Department of Education's Teacher Quality Enhancement (TQE) programs, specifically focus on developing collaborative partnerships between institutes of higher education and K-12 school districts. Collaboration is a central tenet in the reform movement of science teacher preparation. It has been identified as a key element in individual teacher change (Briscoe & Peters, 1997; Briscoe & Prayaga, 2004; Fullan, 2007; Roth & Tobin, 2002) and a key component in PD (Henderson, Beach, & Famiano, 2009; D. W. Sunal et al., 2001; Wright & Sunal, 2004).

This review examines the key characteristics of collaboration, the barriers to effective collaboration, and research focused on collaborative relationships involving physics faculty with a specific emphasis on co-teaching. Mattessich and Monsey (1992) in a literature review of successful collaboration across health, social science, education and public affairs sectors defined collaboration as:

> A mutually beneficial and well-defined relationship entered into by two or more organizations to achieve common goals. The relationship includes: a commitment to: a definition of mutual relationships and goals, a jointly developed structure and shared responsibility; mutual authority and accountability for success: and sharing of resources and rewards. (p. 11)

Mattessich and Monsey identified 19 factors that influence successful collaboration in the six areas of environment, membership, process/structure, communication, purpose and resources. Among the top factors were: a history of collaboration in the community, mutual respect, appropriate cross section of members, collaboration identified as in the members' self-interest, members' ownership in both the process and the outcome, open and frequent communication, sufficient funds, and a skilled convener.

Science faculty collaboration.

Fragmentation of teacher education results from lack of effective collaboration between faculty in Colleges of Arts and Sciences and faculty in Colleges of Education. This was a major finding of The National Commission on Teaching and America's Future. Traditionally, within physics teachers' preparation programs, educational departments teach pedagogy courses and physics departments teach content courses with little collaboration between them (McDermott, Heron, & Shaffer, 2005; Mewborn et al., 2002; Otero, 2005). This creates a dysfunction within science teacher education described by Druger and Allen (1998) as

> Few K-12 science teachers ever have science research experiences in their training; yet they attempt to teach students how science works. The true experts in science are research scientists; yet they are at universities, colleges and research institutions, and may have little to do with K-12 science education. (p. 344)

The barriers to these collaborations lie in "long held biases and calcified tradition, coupled with a generous helping of institutional inertia" (Brantley-Dias, Calandra, Harmon, & Shoffner, 2006, p. 33). Often the difference in the way each college views teaching and learning causes collaboration efforts to be prone to discord (Trubowitz, 2004; Zeidler, Sadler, Simmons, & Howes, 2005). Additionally, the university rewards system weighs faculty's research over their teaching, disadvantaging faculty members who pursue teaching excellence on their own or in cross-college collaborations (W. A. Anderson et al., 2011; Hilborn et al., 2003; Powell, 2003). To overcome this 'institutional inertia', outside stimulus is often needed in the forms of grants (Ballone-Duran, Czerniak, & Haney, 2005; Brantley-Dias et al., 2006; McLoughlin & Dana, 1999), leadership initiatives (Mewborn et al., 2002; Sanders, 2004), or external communities such as professional organizations (Briscoe & Prayaga, 2004; Henderson, 2012; Hilborn et al., 2003).

The majority of collaboration studies, involving faculty in the Colleges of Arts and Sciences found in the literature, focus on partnerships between institutions of higher education and K-12 school districts (Clifford et al., 2008; Hestenes & Jackson, 1996; Massod, 2007). Terming these "K-20 partnerships," Clifford, Millar, Smith, Hora, and DeLima (2008) conducted a meta-analysis of empirical studies focused on these partnerships. The key characteristics of a successful partnership Clifford et al. reported were "(a) leader will and endorsement, (b) shared purposes and goals, (c) open communication, (d) established governance structure, (e) adequate resourcing, and (f) trust" (p. 12). These closely alignment to the broader multi-field collaboration study by Mattessich and Monsey (1992) detailed earlier.

Research on the change within individual science professor's conceptions and practices of teaching and learning resulting from collaboration is limited (Fedock, Zambo, & Cobern, 1996). Those found often emerged from efforts of scientists working with educators to try and improve K-12 science education (Barinaga, 1991; Fedock et al., 1996; Roth & Tobin, 2002). Scientists often identified current K-12 science education as inadequate and identify poor science teacher preparation as the largest cause (Ballone-Duran et al., 2005; Druger & Allen, 1998). Scientists expressed interest in helping to reform science teacher preparation, but when collaborating with science teachers were often confronted with the ineffectiveness of their methods on science teachers. This challenged their conceptions of science education. Through interactions and conversation about effective science teaching with the teachers, scientists must express and reconstruct their beliefs about science teaching, resulting in change (Fedock et al., 1996; Peterman, 1993; Roth & Tobin, 2002).

Studies of smaller collaborations between science faculty and science education faculty in reforming teacher education classes often focused on resulting student change (Briscoe & Peters, 1997; Duran, McArthur, & Van Hook, 2004). One unique follow-up collaboration to designing reformed courses between science and science education faculty was having the science education faculty member support the science faculty member in the teaching of the course (Ballone-Duran et al., 2005; Briscoe & Prayaga, 2004; Duran et al., 2004). One of these studies on a collaboration between a physics professor and science education professor, particularly relevant to my study, is considered in more detail.

Briscoe and Prayaga (2004) detailed the authors' collaboration as science education professor and physics professor in redesigning a college physics course for middle and elementary school pre-service teaching. They reported initially the physics professor's teacher-centered views on teaching and learning limited changes in his classroom. Through the collaboration, reflections between the physics professor and science education professor enabled the physics professor to begin constructing new beliefs, influenced by learning how to listen to the language of his physics students. These new beliefs were accompanied with a shift in the classroom from exclusively teacher-centered to more student-centered. They identified the keys to the successful collaboration as the development of common language, trust between participants, and respect for each other's values and belief. The intrinsic motivation of the physics professor to improve was critical to developing the collaboration. The physics professor experiencing an external community of collaboration between scientist and educators at a conference was highlighted as a key external factor. Briscoe and Prayaga identified collaboration as a complex process influenced by internal and external factors.

Co-teaching.

Collaborations in co-teaching of courses are an effective form of PD for promoting instructional change (Henderson et al., 2009) and student learning (Bacharach, Heck, & Dahlberg, 2010; Kluth & Straut, 2003). Co-teaching is based on a cognitive apprenticeship model which focuses on the knowledge and processes expert teachers use in a variety of real world contexts. Beyond the domain knowledge of a subject, it involves the strategic knowledge needed to solve real world problems. The methods of cognitive apprenticeship (modeling, coaching, scaffolding, articulation, reflection, and exploration) are designed for gaining an integrated skill set, to become mindful of how to use their own problem solving skills, and to gain autonomy in the use of the skills (Collins, 2006). Co-teaching involves two teachers "working together with groups of students and sharing the planning, organization, delivery, and assessment of instruction as well as the physical space" (Bacharach, Heck, & Dahlberg, 2007, p. 19). Co-teaching is widely used within special education in K-12 (Murawski & Swanson, 2001; Scruggs, Mastropieri, & McDuffie, 2007) and to a lesser extent in teacher preparation programs in higher education especially special education (Bacharach et al., 2010; Cook & Friend, 1995; D. Palmer, 2008). These arrangements model and teach collaboration, offer multiple perspective to the students, and encourage growth in the instructors through co-planning and reflection on their teaching (Bacharach et al., 2007). Roth and Tobin (2001) developed the practice in science teacher preparation as an effective means to bridge the gap between teaching theory and praxis and developing future teacher's tacit knowledge.

Co-teaching collaborations within Colleges of Arts and Science or between Colleges of Arts and Sciences and Colleges of Education are limited. Henderson, Beach, and Famiano (2009) presented a study of co-teaching between physics faculty members examining two semesters of a reformed calculus-based physics course. The first semester was co-taught between a new physics professor and an experienced physics professor, who was also a PER researcher. The second semester was taught independently by the new physics professor. Henderson et al.'s findings based on interviews and observations showed a change in the new physics professor's beliefs on teaching and instructional practices changed over the course of the collaboration. The new faculty member expressed changes in his beliefs over the course of the interviews and continued to use reformed instructional practices (RBIS) in his independent teaching. Key factors in the collaboration were similar beliefs between the physics professors on student learning, collegial, cooperative relationship, and mutual reflection on the teaching. The study was limited with observations conducted only during the co-teaching and not during the independent teaching. Using a prior designed course limited the freedom of the new professor and factored heavily into the new professor's showing no change in his instructional practices. In the second semester, all the changes the new professor instituted were changes toward a more traditional course structure.

Bailey and Nagamine (2012) presented a case study of co-teaching between an astronomy professor and a science education professor in an introductory astronomy class. Through the collaboration, the two faculty members redesigned the course to include more learner-centered instructional strategies. The science education professor taught the first section of the course with the astronomy professor observing and participating when needed. This was followed by a second section where the roles were reversed. A conceptual change in the astronomy professor was documented through interviews and observations, showing a motivation to change stemming from personal relevance, social context and high need for cognition. Key factors in the astronomy professor's changes were attending a teacher workshop, the support and modeling of the science education professor, and the positive change in student learning. The continual use of learner-centered strategies beyond the collaboration period by the astronomy professor, including extending it to other courses and faculty members, was discussed. The astronomy professor reported continuing to use learner-centered strategies on his own in the next term and in other classes; no direct observational evidence of this was provided (Bailey & Nagamine, 2012).

A brief description of co-teaching was highlighted in a study documenting the reforming of an electricity and magnetism course at the University of Colorado. A non-PER instructor paired with a PER instructor for one semester. The results appeared inconclusive. The non-PER instructor reported improvements in his teaching; however, he did not associate it with the team teaching. The PER instructor reported having to invest less in the course due to sharing the responsibility (Chasteen, Pepper, Pollock, & Perkins, 2012).

Additional research studies on co-teaching involving physics faculty were not found. The findings discussed indicate a potential for co-teaching to influence and change physics teachers' conceptions and practices, but are full of internal and external challenges.

Alternative collaborative relationships.

Collaborative relationships between Colleges of Arts and Science faculty and College of Educational faculty found in the literature underscored the importance of trust and commitment with complementary goals in the collaboration and the potential for transformations in the collaborators (Brantley-Dias et al., 2006; Marshall, Conana, Maclon, Herbert, & Volkwyn, 2011). More general collective collaborations involving science faculty included collaborative teams and science learning communities (Krockover, Shepardson, Adams, Eichinger, & Nakhleh, 2002; Mewborn et al., 2002; O'Meara & Braskamp, 2005). These efforts were centered around a community of practice focused on teacher education. Community of practice was defined by Wenger (1998) as "members of a community informally bound by what they do together…and by what they have learned through their mutual engagement in these activities" (para. 8). Beliefs were shared publicly. Cognitive dissonance, similar to the conceptual change concept of creating dissatisfaction and lowering the status of an idea, was created from discussing, reflecting, and observing alternative methods. Ideas were then reconstructed in light of effective teaching and learning in a specific context (e.g. college science classroom). This process was both continuous and iterative (D. W. Sunal et al., 2001). Collaborations which focused on teaching and learning allowed the participants to move outside their discipline and reflect on their beliefs about teaching and learning (Jacobs, 2007). Reflection by teachers on their practices often required them to confront their beliefs and ultimately change both their beliefs and practices. However, this is a slow process with beliefs often resistant to change. In addition, departmental and university environments are often restrictive in attitude and practice toward these collaborative partnerships (Wright & Sunal, 2004). Even if teachers, enculturated in this environment, make internal changes in their beliefs, the environment provides strong situational constraints. Instructors must adopt these new innovations and techniques in the context of their traditional environment. This assimilation may never fully extend to the classroom, leading only to incremental change and resulting in limited effectiveness with an abandonment of the new practice (Henderson & Dancy, 2008; Henderson, Dancy, & Niewiadomska-Bugaj, 2012; Vermunt & Endedijk, 2011).

These barriers reinforce the importance of collaboration between both the science community and the educational community for developing common language, trust, and respect for each other. As argued, this is especially critical in science teacher education. For "teacher education is the responsibility of both the College of Education and the College of Arts and Sciences. Without collaboration, real changes in teacher education are unlikely to occur" (Ballone-Duran et al., 2005, p. 179).

Summary of Literature Review

While most studies point toward positive change resulting from collaboration, the research literature is limited, lacking rigorous studies, direct observation of change in the classroom, and in-depth studies of the change process within the collaborators during the collaboration.

With mounting evidence of the ineffectiveness of college science teaching to retain science majors, to attract new science majors, or to properly prepare future teachers, the outside pressure grows to reform college science education along with K-12 science education (NRC, 1996, 2012a; Singer et al., 2012; D. W. Sunal et al., 2004; Tobias, 1990). For this review, I chose specifically to look at the factors involved with college science faculty becoming more reform-based in their conceptions and practices of teaching and learning. In the examination of PCK, knowledge for science teachers was found to be distinctive from knowledge of a scientist (Magnusson et al., 1999; NRC, 1996). Along with science content knowledge, science teachers need to have knowledge of both students' understandings of specific science topics and instructional strategies for teaching science, knowledge most scientists do not have. Bransford et al. (2000) pointed out just because one is an expert in a field does not mean he or she can effectively teach or instruct others how to teach. Evidence of this was shown in a number of studies of the collaboration between scientists and teachers (Barinaga, 1991; Roth & Tobin, 2002)

In examining learning environments, barriers to implementing reformed teaching were present at every level. Epistemological beliefs about teaching and learning were heavily influenced by professors' experiences as students and limited physics faculty's willingness to embrace or even try reform practices in their classrooms. An environment of autonomy in physics departments led to teaching practices carried on independently and in isolation of others. Also limiting was the traditional university's reward system of a culture biased toward disciplinary research over teaching and scholarship of teaching and learning.

Effecting change in this environment was through PD. Research studies indicated that teacher change is an individual experience and cannot be separated from the individual and his or her beliefs, knowledge, and motivation. One of the more promising PD change agents identified was collaboration between Colleges of Arts and Sciences and Colleges of Education as proposed by a number of reforms (Kaplan & Edelfelt, 1996; PhysTEC, 2013). The impact of such PD on faculty change has been theorized to be widespread ranging from their personal beliefs and practices, to their classroom, to their wider learning environments, to the learning of their students, and long term to preservice teachers (C. S. Sunal et al., 2008).

Despite the volume of the literature on PD, my review confirmed many previous researchers' claim that there is still a lack of evidence that shows clear links between PD and long term changes in teacher improvement or student learning (Garet et al., 2001; Weimer & Lenze, 1994). With physics faculty, the evidence was even scarcer. While several general studies showed a possible link between PD and short term changes in college faculty teaching beliefs and practices (Fedock et al., 1996; Gibbs & Coffey, 2004; Ho et al., 2001; Loucks-Horsley & Matsumoto, 1999), the few studies that looked at long term change showed small gains, at best, with most not being statistically significant (Henderson, 2012; Postareff et al., 2008).

The limited research found on collaboration between scientists and educators overwhelmingly focused on the interaction of professors or scientists and elementary science teachers or pre-service K-8 science teachers (Ballone-Duran et al., 2005; Barinaga, 1991; Briscoe & Prayaga, 2004; Gibbs & Coffey, 2004; Roth & Tobin, 2002). Co-teaching, while viewed as effective and widely used in fields of special education and teacher preparation, was rarely utilized between Colleges of Arts and Science and College of Education. In the few cases documented, it appears effective in the context of the presented studies. The theme which emerged was "undergraduate science faculty have benefitted from professional development on teaching" (D. W. Sunal et al., 2012, p. 3). Yet, all the literature reviewers pointed out there is an overwhelming need for more rigorous research studies both quantitative and qualitative in this important area (Henderson, Beach, & Finkelstein, 2011; Levinson-Rose & Menges, 1981; C. S. Sunal et al., 2008; Weimer & Lenze, 1994)

College physics professors play critical roles in the development of future physics teachers and professors. In physics faculty's undergraduate classrooms, future physics teachers and professors learn how to teach, develop their PCK, and form beliefs about teaching and learning which may largely determine the learning environment of their classrooms. Yet, the majority of college physics professors espouse novice views of teaching and learning in light of current research. While change appears possible through collaboration with science education experts, the process is mostly unsubstantiated in the literature. Within this context, I situated my research study of the change process in a physics professor's teaching conceptions and practices on teaching for conceptual change during a collaboration with a science education professor in developing and teaching a physics course for pre-service secondary teachers, emphasizing teaching for conceptual change.

Theoretical Framework

In the literature review section, an overwhelming need for change was identified in the disconnect between traditional college physics teaching practices and beliefs and modern research-based teaching and learning theory. This section examines different frameworks for teacher change and identifies a theoretical framework. To capture the complex, multilayered nature of educational change, leading teacher-change theories, linked with large scale organizational change and small scale conceptual change, are examined through the lens of this theoretical framework.

Educational Change

Educational change is a complex process occurring and interacting at organizational, classroom, and individual levels. Change is about shared meaning involving both individual change and social change. The socio-political process involved in change represents the big picture. The small picture is the phenomenology of change where meaning involves both cognitive and affective dimensions. Both of these dimensions must be developed and linked. Therefore, effective educational change results from actions that change teacher practices which involve teachers' beliefs, pedagogy, and resources (Fullan, 1999, 2007). When new innovations fail to affect teacher's conceptions of teaching and learning, little change occurs (Elmore, 1996).

Teacher change has historically been linked with PD (Clarke & Hollingsworth, 2002; Guskey, 1986). The three key aspects to teacher change resulting from PD are changes in teachers' beliefs, changes in teachers' classroom practice, and changes in student learning (Clarke & Hollingsworth, 2002; Desimone, 2009; Guskey, 2002). These aspects have been shown to be interrelated showing a cyclical nature of change, and each representing a potential starting point for change (Clarke & Hollingsworth, 2002; Cobb, Wood, & Yackel, 1990; Huberman, 1992). A key link between these aspects in bringing about change is teacher reflection. Teachers reflect on their own and others' beliefs and practices and then reconstruct these beliefs and practices based on arguments and new instructional experiences (V. Richardson, 1990).

Teacher change models.

The traditional teacher change model resulting from PD focused on changing teachers' attitudes, beliefs, and perceptions with the belief that these changes lead to changes in classroom practices, resulting in greater student learning. Guskey (1986) presented an alternative model (See Figure 3) of teacher change where teachers' classroom practices were the first to change.

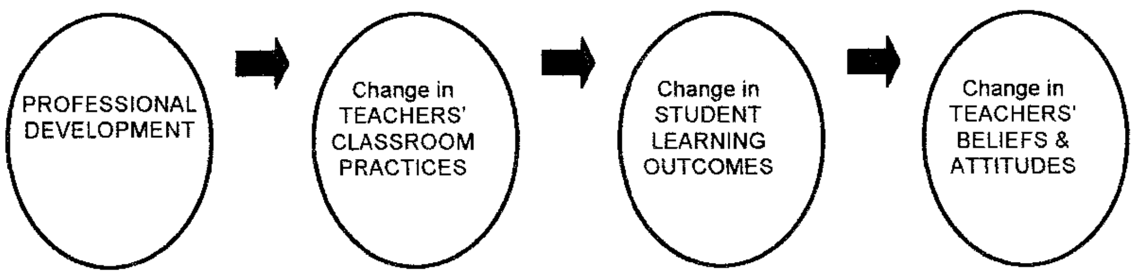


Figure 3. A Model of Teacher Change. Adopted from "Professional Development and Teacher Change," by T. Guskey, 2002, *Teachers and Teaching: Theory and Practice, 8*, p. 383. Copyright 2002 by Taylor & Francis Ltd.

In each of these theoretical models of teacher change the core elements were the same and nearly universal in conceptual and empirical studies of PD (Desimone, 2009). These change models have been criticized for being too simplistic with severe limitations. Specifically, both the traditional change model and Guskey's model restricted change to a linear progression. The Desimone model (Figure 4), while allowing different emphasis on the key elements due to its non-recursive, interactive pathways, favored a simple progression due to its rectilinear construction. Therefore, a more sophisticated model is required to accurately capture the complexity of teacher change (Cobb et al., 1990; Huberman, 1992).

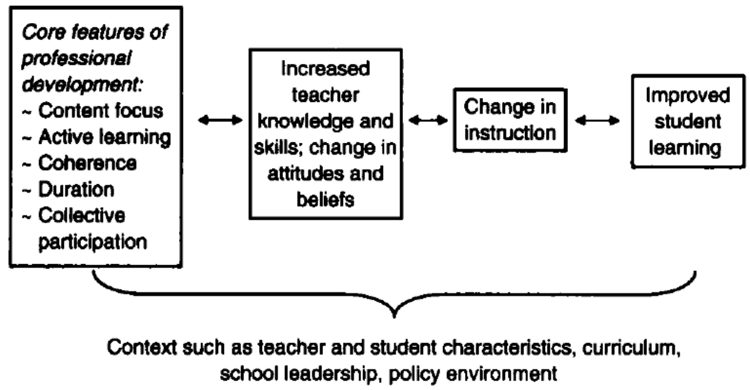


Figure 4. The Path Model of a Core Conceptual Framework. Adapted from "Improving Impact Studies of Teachers' Professional Development: Toward Better Conceptualizations and Measures," by L. Desimone, 2009, *Educational Researcher, 38,* p. 185. Copyright 2009 by American Educational Research Association.

Interconnected Model of Teacher Professional Growth

The Interconnected Model of Teacher Professional Growth (IMTPG) incorporates all of core elements of teacher change in a more robust and flexible framework (Clarke & Hollingsworth, 2002). The IMTPG model based on four similar analytical domains holds that:

> Change occurs through the mediating processes of 'reflection' and 'enactment', in four distinct domains which encompass the teacher's world: the personal domain (teacher knowledge, beliefs and attitudes), the domain of practice (professional experimentation), the domain of consequence (salient outcomes), and the external domain (sources of information, stimulus or support). (Clarke & Hollingsworth, 2002, p. 950).

In the diagram of the IMTPG (Clarke & Hollingsworth, 2002) shown in Figure 5, the shapes of the domains distinguished the external domain (ED) from a teacher's personal world comprised of the personal domain (PeD), domain of practice (DP), and domain of consequences (DC).

Change can occur in any of the four domains and will distinctly reflect the domain where it occurs.

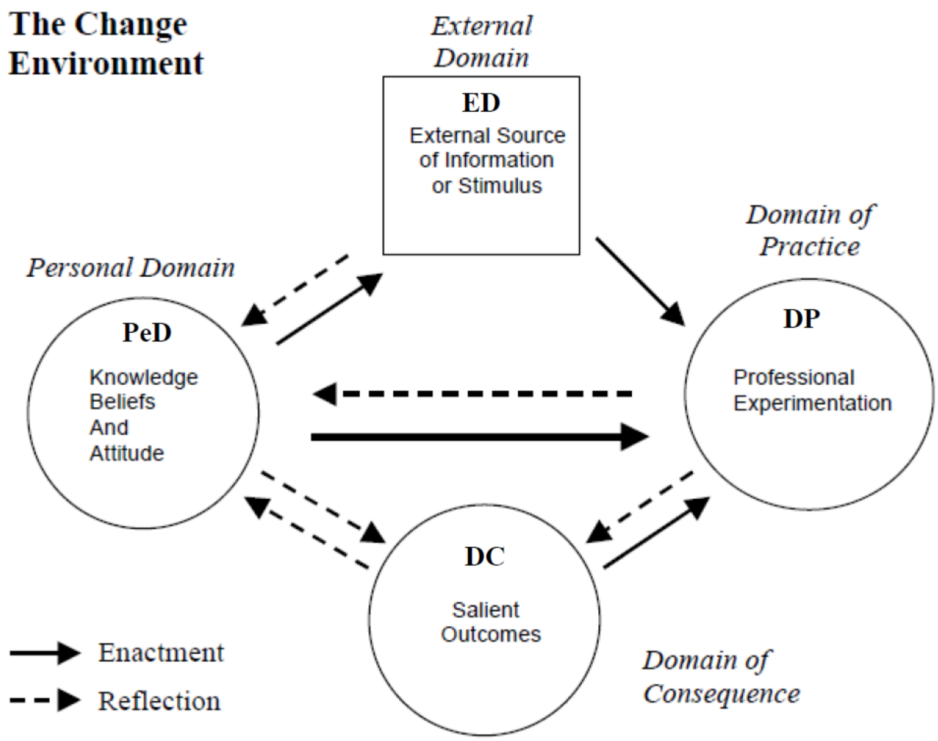


Figure 5. The Interconnected Model of Teacher Professional Growth. Adapted from "Elaborating a Model of Teacher Professional Growth," by D. Clarke and H. Hollingsworth, 2002, *Teaching and Teacher Education, 18,* p. 951. Copyright 2002 Elsevier Science Ltd.

The two mediating processes of reflection and enaction (represented by a dashed arrow and a solid arrow, respectively) are the means of translating change in one domain to another domain. The mediating process of reflection in the IMTPG is based on the Dewey idea of reflection being "active, persistent, and careful consideration" (Clarke & Hollingsworth, 2002, p. 954) and captures the critical role of teacher reflection in teacher change (V. Richardson, 1990). The model indicates five possible reflection links (dashed arrows): ED →PeD, DP→DC, DC→PeD, PeD→DC, and DP→PeD. The second mediating process of enaction distinctly refers to the "translation of a belief or a pedagogical model into action from simply 'acting', on the ground that acting occurs in the domain of practice, and each action represents the enactment of something a teacher knows, believes or has experienced" (Clarke & Hollingsworth, 2002, p. 951). Four enactment links (solid arrows) are identified: ED→DP, PeD→DP, DC→DP, and PeD→ED.

Clarke and Hollingsworth identified distinctions between two patterns in teacher growth: change sequences and growth networks. Change sequences involved two or more domains connected by reflective or enactive links supported by empirical data. This change is considered temporary involving as little as one instance. Growth network denoted more lasting change and exhibited explicit evidence of lasting change in teacher knowledge or beliefs or a change in practice.

A model's true measure is based on its effectiveness in analyzing, predicting, and explaining its targeted phenomenon. Clarke and Hollingsworth's (2002) foundation for ascribing these characteristics to the IMTPG was based on three empirical studies of Australian teachers. In applying the IMTPG in these studies, Clarke and Hollingsworth demonstrated the model's ability to accommodate alternative pathways of professional growth. Justi and van Driel (2006), in their study of beginning teachers' knowledge development of models and modeling, demonstrated the robustness of the IMTPG, not only in designing a PD project but also analyzing and understanding the changes in teachers' knowledge resulting from the project. They concluded that the IMTPG, "made possible the characterization of the teachers' knowledge development as an idiosyncratic process" (p. 449). Goldsmith, Doerr, and Lewis (2014) utilized the IMTPG model for a meta-analysis of 106 articles on the professional learning of mathematic teachers and confirmed the model's "articulation of the incremental, iterative, multi-domain nature of teacher learning" (p. 20).

Comparing the IMTPG model to the earlier change models, the IMTPG had the capacity to accommodate these models within its structure but was sophisticated enough not to exhibit the same limitations. The IMTPG allowed for the non-linear progression and multiple growth pathways between all the core elements in a robust and flexible framework, centered on the mediating processes of reflection and enaction. Further, the IMTPG distinguished the external domain, consisting of the larger change environment, from the three domains of the teacher's world (personal, practice, and consequence). This distinction acknowledged the constraining or facilitating role the cultural context a teacher works within had on teacher change. With these features, the IMTPG appears to be a powerful framework for modeling the main elements of teacher change identified from the literature.

Organizational change.

The external domain component of the IMTPG allowed the situating of teacher change within the bigger picture of organizational change. Organization change focused on understanding why organizations behave as they do and discovering which forces need to be strengthened or weakened to bring about change (Burnes, 2004). The forces of equilibrium within a group often constrain individual behavior into conforming with group norms. An educational example is the difficulty of individual faculty members to change their teaching practice within a department resistance to change. With large scale change at the organizational level, change was seen as complex (Fullan, 1999; Stacey, 1995), but containing recognizable patterns identified by different theories (Burnes, 2004; Lewin, 1951; Schein, 1999; Stacey, 1996; Weick & Quinn, 1999). The IMTPG modeled this interplay between organizational change and individual change by the two domains of the external domain and the personal domain. Between these domains an enacting mediating process was shown from the personal domain to the external domain. This modeled an individual acting on his or her beliefs which influenced the change in the organization. Likewise, an individual reflecting on organizational change can bring about change in his or her personal domain of knowledge, beliefs, and/or attitudes.

Conceptual change.

Change within the personal domain of knowledge, beliefs, and attitudes represents small scale change and a complex system with recognizable patterns emerging in conceptual change. The conceptual change model (Posner et al., 1982; Strike & Posner, 1992), proposed in order for a person to change his or her conceptions had three conditions that must be met: intelligibility, plausibility, and fruitfulness. The concept must be understood by the learner, based on his or her current knowledge (intelligibility). The concept must be believed as true (plausibility). The concept must be useful for the learner (fruitfulness). If a concept meets all three conditions, then learning can proceed. However, if the concept conflicts with a learner's preconception then it will not be plausible and fruitful until the learner becomes dissatisfied with his or her prior conception (Hewson, 1981; Hewson & Hewson, 1988; Posner et al., 1982; Strike & Posner, 1992). Gunstone and Northfield (1986) summarized the process as "'if the change doesn't make sense to students, it won't happen'; 'change is more likely when students feel the problem is significant to them'; 'change produces anxiety in students'" (p. 6).

As conceptual change theory has developed so has its complexity. Currently, several different perspectives have been proposed as frameworks for explaining conceptual change. These fall in three general classifications – epistemological, ontological, and social/affective.

Epistemological perspective.

The epistemological perspective focuses on how a learner thinks about his or her knowledge about the concept being considered. Key distinctions of students' preconceptions as coherent theories (McCloskey, 1983); coherent, organizing presuppositions (cognitive view); or primitive, non-coherent reasoning elements (knowledge as elements view). In the cognitive view, concepts are embedded in a large theoretical framework and consist of three main parts: a naïve framework theory of physics, specific theories, and mental models (Vosniadou, 1994). The most well-known "knowledge as elements" perspective was diSessa's (1993) theory of phenomenological primitive or p-prims. P-prims are small knowledge structures that originate in interpretations of experienced reality. They act by being recognized in a physical situation. diSessa described the role of learning as providing the context where "p-prims are activated in appropriate circumstances and, in turn, they should help activate other elements according to the context they specify" (diSessa, 1993, p. 112). In this view, conceptual change is an evolutionary process in which these elements (p-prims) and interconnections are re-contextualized with many coordinated changes needed to arrive at a normative scientific view (diSessa, 2008).

Ontological perspective.

The ontological perspective looks at how the student perceives the nature of the concept being considered and classifies the concept into ontological categories. Conceptual change is assumed to occur when a concept is re-assigned to an ontologically distinct category. This requires that the student be aware that a shift is needed and the correct category is available (Chi, 2008; Chi, Slotta, & de Leeuw, 1994). For example, heat is often classified by students as a thing while scientists classify it as a process. So for conceptual change to occur with students' ideas on heat, students must first recognize the different classification of heat.

Social/Affective perspective.

The social/affective perspective examines the conditions outside the learner's cognition, such as the environment and emotions, and their influence on the conditions for change (Sinatra, 2005; L. M. Tyson et al., 1997). This perspective focuses on how affective factors such as students' motivation and the classroom context, influence students' dissatisfaction with conceptions (Pintrich, Marx, & Boyle, 1993). Models derived from this perspective focus on how motivation and degree of engagement determine the type and extent of conceptual change in an individual (Dole & Sinatra, 1998; Gregoire, 2003).

Complex system perspective.

This multiplicity of theories and evidence strongly support the complexity of conceptual change. Brown and Hammer (2008) proposed a model of conceptual change as a complex system. In this view, conceptual change reflected the characteristics of intrinsic dynamism, non-linearity, emergent structures, and embeddedness found in complex systems. A complex system is often a part of a larger system and at the same time is made up of smaller complex systems.

Studying conceptual change is analogous to material analysis where a material can be studied on a macroscopic, microscopic, or atomic level ("grain size"). At each level, complex elements and interactions are occurring. With conceptual change, social and affective factors could be viewed as dynamics at a larger "grain size" or level of organization. Cognitive factors, such as ontological categories, framework presuppositions, or p-prims, represent other dynamics at smaller "grain size" levels of organization.

Conceptual change theory is complex; yet, in its complexity patterns have emerged which have been described by different conceptual change theories. The IMTPG, in its simple framework but robust arrangement, allows this complexity of conceptual change model perspectives to be modeled. Conceptual change models can help explain the dynamics of what occurs within the personal domain aspect of the IMTPG, involving changes in knowledge, beliefs, and attitudes. The attitude element encompasses the affective perspective. Further, the mediating processes between the external domain and the personal domain allow the contextual influence of the environment to be examined. With these features, the IMTPG appears to be a powerful framework for modeling teacher change, representing the key aspects or domains of teacher change, the complex interrelatedness to environment and macroscopic organizational change and the more microscopic complex cognitive and affective dimensions of conceptual change.

Concerns-based adoption model.

A key factor in educational change is that there must be a coherency between the organization, the individuals, and the change innovations (Ellsworth, 2000; Fullan, 2007). An effective and well-established model for examining the intended adopter in the change process is the Concerns-Based Adoption Model (CBAM) (S. E. Anderson, 1997; Ellsworth, 2000). CBAM focuses on the change of an individual, the evolving of his or her thinking (stages of concern), and his or her utilization of the change (levels of use) during the change process (Hord, Rutherford, Huling-Austin, & Hall, 1987). CBAM is based on five key assumptions:

(1) change is a process, not an event;
(2) change is accomplished by individuals;
(3) change is a highly personal experience;
(4) change involves developmental growth in feelings and skills; and
(5) change can be facilitated by interventions directed toward the individuals, innovations, and contexts involved. (S. E. Anderson, 1997, p. 333)

CBAM key characteristics focused on the importance of assessing and attending to where individuals are in the change process, addressing their questions and stressing the importance of monitoring the implementation of change over several years. CBAM utilized diagnostic tools to measure change. The Stages of Concerns (SoC) instrument defined seven levels of progression: awareness, informational, personal, management, consequence, collaboration, and refocusing. From these levels the SoC generated an individual's concern profile for a specific time in the change process (Hall, George, & Rutherford, 1998; Hord et al., 1987; Loucks-Horsley et al., 1996).

In a critique of the CBAM model, Anderson (1997) pointed out its robustness and empirical grounding in modeling the implementation of change, but its limitations in explaining teacher change. Anderson remarked that there is a current need for theories that "account for variable patterns of change within user organizations" (p.363). One approach suggested was integrating the CBAM diagnostic tools with other theories of learning and change (S. E. Anderson, 1997; Hord et al., 1987). This remains largely "unchartered territory" (S. E. Anderson, 1997, p. 360). The IMTPG represented such a theory. Examining the key assumptions of both theories showed a general agreement. As discussed, the IMTPG offered a framework for explaining, predicting, and analyzing the complex, nonlinear change of individuals.

Conclusion

Situating my proposed study of the change process of a physics professor in response to the change innovation of collaboration with an education professor within the discussed change theories revealed some essential considerations. First, change is complex as shown in all three levels of change: organizationally, conceptually, and individually. Secondly, the change process is interconnected as both the organizational environment and the individual's beliefs restrain and facilitate the degree an individual will experience change. Thirdly, change is an individualistic, idiosyncratic process another distinction of complex theory.

As discussed, the IMTPG provides the best framework for explaining, predicting, and analyzing the change in an individual. The IMTPG with its four core domains captures the key elements identified in the literature on teacher change. Incorporating the CBAM's SoC diagnostic tool within the IMTPG offers a way to more empirically ground where the individual is in the change process at a given time and to better document the ongoing change. Therefore, the IMTPG will be used as the theoretical framework for my study with the conceptual framework of the CBAM's SoC diagnostic tool.

Research Questions

How is teaching for conceptual change conceptualized and practiced by a physics professor during and beyond an extended collaboration with a science education professor focused on teaching for conceptual change?

Related Questions

1. What is the evidence of change in a physics professor's conceptions of teaching for conceptual change?
2. What is the evidence of change in a physics professor's practices of teaching for conceptual change?
3. What are the learning-environment characteristics identified by the physics professor that either facilitated or hindered changes in his conceptions and/or practices in teaching for conceptual change?

3 METHODOLOGY

Overview

Qualitative research involves naturalistic approaches, seeking to understand phenomenon in all their complexity in context specific settings, generating data which provides depth and detail (Bogdan & Biklen, 2006; Norman K. Denzin & Lincoln, 2000; Hoepfl, 1997; Patton, 1990). My research question, based on a context-specific setting encompassing the complexity of an individual's conceptions and practices, dictates a qualitative research study (Becker, 1996). The research question that my methodology sought to answer was: How is teaching for conceptual change conceptualized and practiced by a physics professor during and beyond an extended collaboration with a science education professor focused on teaching for conceptual change and its related sub-questions:

1. What is the evidence of change in a physics professor's conceptions of teaching for conceptual change?
2. What is the evidence of change in a physics professor's practices of teaching for conceptual change?
3. What are the learning-environment characteristics identified by the physics professor that either facilitated or hindered changes in his conceptions and/or practices in teaching for conceptual change?

An overview of the qualitative research methodologies, most applicable to these questions and the rationale behind these choices, is now discussed.

Phenomenography

A phenomenographic approach, focusing on the variation in the ways a phenomena is experienced, provides the theoretical underpinnings of the study (Akerlind, 2008; Pang, 2003).

Phenomenography developed from empirical studies on learning in the early 1970s conducted by Ference Marton and his associates at the Department of Education and Educational Research in Gothenburg, Sweden. Marton defined phenomenography as “the empirical study of the limited number of qualitatively different ways in which various phenomena in, and aspects of, the world around us are experienced, conceptualized, understood, perceived and apprehended” (Marton, 1994, p. 4424).

Phenomenography is a “second order perspective” aimed at people’s conceptions of phenomena, with a conception being “the experienced meaning of one specific part of the surrounding world” (Svensson, 1989, p. 531). A person’s awareness of these conceptions contains both a “what” aspect centered on the object and a “how” aspect involving the act, making conceptions dynamic dependent on both the individual’s activity and the reality of the world external to the individual. Therefore, conceptions are context dependent, neither completely naturalistic nor subjective (Entwistle, 1997; Harris, 2011; Hasselgren & Beach, 1997; Marton, 1981, 1994; Svensson, 1997; Ulgens, 1996).

A fundamental assumption of phenomenography is that reality or phenomena is represented in human thinking as different conceptions or entities as a whole, demarcated from but still related to its surroundings. Knowledge then is the differentiation of these whole descriptions or conceptions (Marton, 1981; Svensson, 1997). To experience a distinguishable concept requires not only that it be identified as a whole from its context (the meaning aspect of a conception), but that its parts and relationship between them must also be discernible. This is identified as the structural aspect of a conception and must occur simultaneously with the distinguishing of the concept as a whole (Harris, 2011; Marton & Booth, 1997; Pang, 2003). Using the idea of a lamp, an object identified as a lamp must also be seen to have a switch, bulb, shade, and various parts. All parts contribute to the concept of a lamp or the structural aspects of the concept. "Structure presupposes meaning and meaning presupposes structure. Structure and meaning thus mutually contribute to each other in the act of experiencing" (Pang, 2003, p. 149).

From these characteristics of phenomenography, Pang (2003) distinguished two types of variation within the phenomenography-research tradition. The first is the discovery of all the understandings people have of specific phenomenon, sorting them into qualitative conceptual categories (Marton, 1981, 1986, 1994). Examples of these types include Prosser, Trigwell, & Taylor's (1994) study on university chemistry and physics teachers' conceptions of teaching and learning; McKenzie's (2003) study of university teachers' conception of teaching change; and Akerlind's (2007) study of university teachers' conceptions of professional growth. These studies, as discussed in the literature review, produce a finite set of categories of how a given phenomenon is experienced.

More recently, variation theory, which focuses on how learners experience a phenomenon as discerned by their identification of critical aspects of the phenomenon, has emerged from phenomenography research. These critical aspects can only be discerned when a learner experiences a variation in the particular aspect. This stems from the idea that learning is a qualitative change in the way one is capable of experiencing some phenomenon (Booth, 1997; Marton, 1981; Svensson, 1997), thus related to a learner's structure of awareness. This learning involves *variation*, *discernment*, and *simultaneity*. Therefore, learning requires variation of the aspects of a phenomenon, previously taken for granted, to become visible. Discernment involves seeing this new variation in a new light. Simultaneity entails seeing at the same time both the previous view of the phenomenon and the new perspective with the variation (Booth & Hulten, 2003; Marton & Booth, 1997; Pang, 2003). Holmqvist (2011) illustrated this with the analogy of an apple. One can determine whether an apple is bitter or sweet compared to tastes of other apples (discernment). One can also link the taste to another aspect of the apple, such as color, and eventually learn to associate the taste of an apple with a specific color of an apple (simultaneity). However, this knowledge of apples is not possible until one experiences a variety of apples (variation). Akerlind (2008) further added the need for *contrast*, where the phenomenon is compared to another experience, to help distinguish it, such as with learning to teaching.

This framework of variation studies has been used within the classroom to analyze classroom teaching and the ways students experience different phenomena in terms of critical aspects and dimensions of variations (Holmqvist, Gustavsson, & Wernberg, 2008; Lam & Tsui, 2013; Ling, Chik, & Pang, 2006; Marton & Tsui, 2004; Pang, 2003; Runesson, 2006). The pedagogical implications from these studies concur in order for learning to take place; "teachers should discern the critical aspects of the phenomena that are being dealt with and of pupils' learning simultaneously, against a backdrop of experienced variation of the aspects concerned" (Pang, 2003, p. 154).

Phenomenography, with its two faces of variation, presented a means of looking at both the variation in how the physics professor conceptualizes teaching for conceptual change and the variation in aspects of how the physics professor experienced teaching for conceptual change. This provided a framework for qualitatively describing the change process in the physics professor, based on his changing conceptions of teaching for conceptual change and the variations within his practice.

Case Study

Since my current research focused on the experience of a physics professor within a specific context, i.e., during a collaboration with a science education professor, a phenomenographical case study was used as my means of representation. A case study is “an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident” (Yin, 2009, p. 16). The case study is distinctive from other qualitative research, based on its use of intensive description to analyze and its emphasis of the three specific features of being: *particularistic*, *descriptive*, and *heuristic*. A case study is *particularistic* when it focuses on a specific event, program, or phenomenon and the researchers focus on uncovering interactions of specific aspects that characterize a phenomenon. The case study is *descriptive* when it provides a rich, thick description of a phenomenon being studied and can help describe the intricacies and complexities of a phenomenon. It is *heuristic* when it can bring knowledge of new meaning, expand the reader’s experience, or confirm what is known of the phenomenon being studied (Merriam, 1998, pp. 29-30). As discussed in the literature review, teacher change is a complex process that is heavily influenced by the context of the surrounding learning environment. The focus of my research was even more particular: focusing on the teacher change of a single physics professor, during a unique collaboration with a science education professor in the specific area of teaching for conceptual change. Based on my research question, the unit of analysis for the case study was the physics professor and the change in his conceptions and practices of teaching for conceptual change during a collaboration with a science education professor (Yin, 2009). This change process of the physics professor is embedded in the learning environments of the physics professor, requiring the intensive description of a case study to illuminate the learning environments' characteristics which facilitated and/or hindered the change. The study is a phenomengraphical case study. Phenomenography is the theoretical lens used in examining and presenting the change in the physics professor through his perspective as captured in his words and actions.

Context of the Study

The research study was conducted with a senior physics professor in the Department of Physics and Astronomy at a research-intensive, urban Southeastern University. It focused on his teaching PHYS 7050 (fictitious course numbers represent the type and level of the actual courses), a graduate level physics course for secondary science teacher candidates. The course combined three essential components for physics teachers' preparation: physics concept acquisition, pedagogical methods through discussion/modeling of conceptual change teaching strategies, and student modeling through practice teaching in an undergraduate studio physics course (PHYS 1080) (Darling-Hammond, 2006; Etkina, 2005). The physics content mirrored an introductory undergraduate physics course (e.g. mechanics) with an emphasis on common student preconceptions (Knight, 2004), but tailored to fit the students' career trajectory as future secondary science teachers. The conceptual change component focused on discussion/modeling of conceptual change teaching strategies as found in current literature (e.g. Clement's (1993) work on bridging analogies, diSessa's (1993) p-prims model, and Slotta and Chi's (2006) ontological misclassification framework). The modeling or practice teaching occurred as the teacher candidates facilitated learning activities to promote the active learning of undergraduate students in PHYS 1080, a studio version of an introductory physics course (Beichner, 2008).

Historical Background

PHYS 7050 was a unique physics course designed in collaboration between a physics professor from the College of Arts and Sciences and a science education professor from the College of Education. The development of PHYS 7050 arose from a need to provide additional physics-content instruction for teacher candidates in the Masters of Arts in Teaching (MAT) secondary science program seeking a broad-field science certification. This collaboration was a direct result of national reforms and policies to overhaul science teacher preparation programs. Specifically, the catalyst was a mini-grant from the University System of Georgia's PRISM initiative, a five-year NSF funded $34.6 million grant to improve educational achievement levels for closing performance gaps in science and math among Georgia students (Jones, 2008). This grant funded collaboration led to the co-teaching of PHYS 7050 in the summer of 2012 by both the physics professor and science education professor. The objectives of the course were: (1) to increase the conceptual understanding of the pre-service teachers to give them the appropriate knowledge base; (2) to heighten the awareness of these teachers regarding the existence and basis of physics misconceptions; (3) to foster the formation of the pedagogical content knowledge required to help students bridge the gap between their everyday views of physics-related phenomena and the scientifically-accepted views; and (4) to accomplish the preceding objectives through a collaboration between faculty members from two different colleges, which would strengthen the knowledge base of each faculty member and serve as a model for future collaborations around course development and implementation (Stoll, Demir, & Criswell, 2012). The PHYS 7050 course was offered again in the summer of 2013 in an eight-week term (13 classes) with the same content and structure, but without the extensive collaboration of the co-teaching. A physics professor was the primary instructor covering both the physics content and teaching for conceptual change portions of the course. The science education professor provided lectures on teaching for conceptual change during the last four classes.

Preliminary Study

A preliminary research study on the initial implementation of PHYS 7050, involving 15 enrolled MAT students and the two professors, was conducted in the summer of 2012. The goal was to assess the effectiveness of the PHYS 7050 in producing pre-service secondary science teachers, who have the capability of facilitating deep conceptual understanding in high school physics students, and the effect of the collaboration on the knowledge and practice of the professors. Data collected included pre- and post- interviews with both professors and all of the students, along with classroom observations and recordings of the class sessions. As part of the three member research team, this preliminary study became the main cultivator for this research study. Pre- and post- interviews with the physics professor revealed a transitioning of beliefs and ideas about students' conceptions and how to effectively teach physics in regards to them (Stoll, Criswell, & Demir, 2014). From this my research questions emerged along with the relevance of conducting a case study of the physics professor's pedagogy in redelivering the PHYS 7050 course. The preliminary study, with its pre- and post- interviews of the physics professor along with the classroom observations and recordings from the summer of 2012, provided a baseline set of data. This data was then compared with the case study of the physics professor's co-teaching PHYS 7050 with the science education professor during the summer of 2013 in order to document changes in the physics professor's conceptions and practices on teaching for conceptual change.

Participants

With the specificity of the research study, a purposive sample was used (Bogdan & Biklen, 2006; L. Cohen, Manion, & Morrison, 2000). The primary participant, Professor Fairbanks (pseudonym), was a physics professor in the Department of Physics and Astronomy from the College of Arts and Sciences. The physics professor was the co-designer and instructor in the initial delivery of PHYS 7050 with a science education professor from the College of Education, Professor Crefeld (pseudonym). Thus, the physics professor offered the best opportunity for intensive study and had the greatest variety of experiences regarding my research questions (Stake, 2000). Due to the specificity of my topic, a wide variety of participants with experiences pertaining to my research questions were not available or desired. As Merriam (1998) points out regarding case study, “If there is no end, actually or theoretically, to the number of people who could be interviewed or to observations that could be conducted, then the phenomenon is not bounded enough to qualify as a case” (p. 28). So, my focus was not on the breadth of individuals’ experiences, but rather the depth of an individual’s experience in the context of a case study.

Prior to the preliminary research study, I developed a relationship with the physics professor by taking two directed study classes under him. Studying physics education and the field of PER with him, I recognized and appreciated his expertise as a physics educator. In the preliminary research study, watching him instruct on similar concepts that I teach to my high school students further increased my respect for him as a physics professor. The mastery he demonstrated of physics and the way he communicated physics concepts to his students, making the complex understandable, made me realize I was observing an expert. Along with my research notes, I recorded personal notes that later helped me better teach physics concepts to my students, emulating the methods of Professor Fairbanks.

In the preliminary study, Professor Fairbanks readily admitted his limitations in teaching the MAT students while showing a strong focus on addressing these limitations and growing as a teacher. In my two interviews with Professor Fairbanks during this study, his eagerness and interest in learning from the science education professor impressed me. Why was a physics professor, who was an expert in his field, so eager to learn from a science education professor? What did he hope to learn? What was motivating him to learn? These questions, many rooted in my own experience, planted the seeds that led to this study.

To understand what the physics professor was learning through this collaboration with the science education professor and how it was changing him required an openness and willingness on his part. It required a vulnerability to be studied and portrayed, not in his expertise, but in his novice learning of becoming a more effective science educator. For a senior-ranking, professor to be open to this would be extraordinary. Yet, Professor Fairbanks' genuine concern for student learning made him personable and approachable to all students and willing to take on new challenges Our past interactions, having established a rapport and mutual respect between us, made both of us open to embarking on this research partnership together. For this study, I provided the physics professor with an informed consent form (See Appendix A) which outlined the procedures, as well as the potential risks and benefits of the study.

While the physics professor was the focus of the research, a second group of subjects were used for an alternative perspective on the class and to help triangulate the results of the class which were all part of a crystallization process. The overall crystallization process is explained more in depth later (Figure 6). The second group of participants were graduate students in the MAT secondary science program enrolled in Physics Principles & Teaching Problems I (PHYS 7050). All MAT students enrolled in PHYS 7050 (n=9) were recruited, but only those consenting to participate were studied. Of those consenting to participate, about half (n=4) were selected to be interviewed, based on further consent. This allowed in-depth, detailed accounts to be gathered from a wide variation of participants, producing both a profile of the unique variations within the class as well as important shared patterns (Patton, 1990).

The recruitment of these volunteers occurred in PHYS 7050 at the beginning of the 2013 summer semester. I presented the research study to the MAT student participants, explaining the purpose of the study and procedures for data collection. MAT students were presented an approved consent form for their participation in the study (See Appendix B).

Data Collection

The goal of my research study, consistent with qualitative research, was to “accumulate sufficient knowledge to lead to understanding” (Lincoln & Guba, 1985, p. 133). My research study was an emergent research design, beginning with specific observations and building toward general patterns in an iterative manner. Data collection and analysis occurred simultaneously and had a reciprocal relationship (Lincoln & Guba, 1985; Patton, 1990; Strauss & Corbin, 1990). This design is now presented through the specific data collection of the project (See Appendix C). A detailed look at the data analysis procedure follows. A visualization of the overall research design and analysis is shown below in Figure 6.

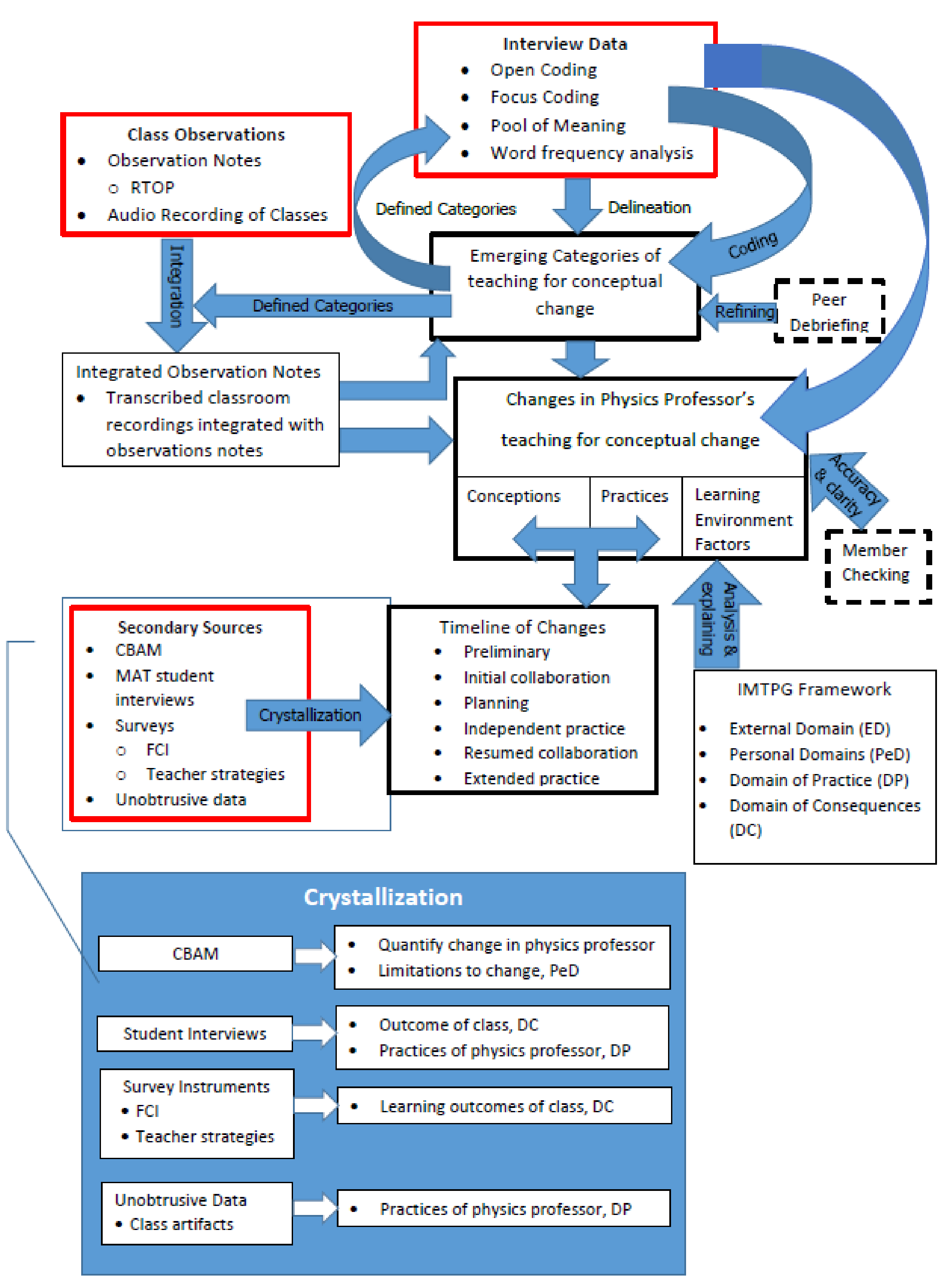


Figure 6. Research Study's Overall Research Design and Analysis Process. Red boxes represent the data sources, the bold black boxes represent findings, and the dashed boxes represent methods for establishing trustworthiness. The blue arrows represent different processes in the iterative analysis. The crystallization process utilizing the secondary data sources is expanded in detail in the blue box.

Primary Data Sources

Following a phenomenographic methodology, interviews were my primary source of data (Booth, 1997; Entwistle, 1997; Marton, 1986). For as Marton and Booth (1997) stated:

> The only route we have into the learner's own experience is that experience itself as expressed in words or acts. We have to ask learners what their experiences are like, watch what they do, observe what they learn and what makes them learn, analyse what learning is for them. (p. 16)

The interviews were semi-structured, allowing the interviewer to follow the line of questions that emerged during the interview rather than a rigid series of questions (See Appendix D). While the interview was guided by a pre-determined framework, it was "open" to allow the interview to develop as a natural conversation, "deep" to allow lines of discussion to be followed until exhausted, and a mutual understanding reached between the interviewer and interviewee (Booth, 1997; Entwistle, 1997; Rubin & Rubin, 2005). Interviews occurred with both the physics professor and the MAT students in PHYS 7050.

Physics professor's interviews.

The physics professor was interviewed extensively during the research study with each interview lasting approximately 45-60 minutes. Five formal interviews were conducted, supplemented by shorter informal discussions as needed. These interviews can be generally classified as background interviews, teaching reconstruction interviews, and reflective interviews. This structure was modeled after a three-interview series advocated by Schuman (1982) for phenomenological interviewing:

> The first interview establishes the context of the participants' experience. The second allows participants to reconstruct the details of their experience within the context in

which it occurs. And the third encourages the participants to reflect on the meaning their experience holds for them. (Seidman, 1998, p. 11)

The initial background or "focused life history" (Seidman, 1998, p. 11) interview occurred prior to the beginning of PHYS 7050. The focus of this interview was to establish the context of the physics professor's experience and to include both his formational experiences as a physics instructor and physics educational researcher (See Appendix D).

The second set of interviews or "details of experience" (Seidman, 1998, p. 12) interviews focused on the physics professor's pedagogy and teaching beliefs, specifically regarding teaching for conceptual change exhibited in his instruction in PHYS 7050. The first interview of this series, the *planning* interview, was conducted during the first week of PHYS 7050. The focus of this *planning* interview was on the physics instructor's teaching goals and philosophies for PHYS 7050 (See Appendix D). The second interview of this series, the *instructional* interview, occurred near the midpoint of the semester. Classroom observations, including field notes and video recording detailed below, were used in preparing for this interview. In this *instructional* interview, the physics professor was questioned about his current pedagogy in PHYS 7050 (See Appendix D). The last interview of the series, the *executional* interview, was conducted at the end of the semester. Specific references, based on classroom observations and audio recordings, were used in preparing for this interview. The focus of this *executional* interview was the physics professor's view on the connection between his teaching pedagogy and actual learning of his students (See Appendix D).

The last physics professor's interview or "reflection on the meaning" (Seidman, 1998, p. 12) interview was conducted after the initial data analysis and findings were established. This *reflection* interview focused on the professor's assessment of the course, but primarily was a reflection on the process and the meaning of it to the physics professor. In addition, key findings from the analysis were referenced for the professor's insight and elaboration, further delineating the change process and grounding it in the professor's perspective, consistent with a phenomenological approach. (See Appendix D). This interview was combined with an open-ended *follow-up* interview conducted after two observations of the physics professor instructing in an alternative course (PHYS 3000) detailed below.

Secondary Data Sources

A common criticism of phenomenography is its sole reliance on interviews as the only data source (J. T. E. Richardson, 1999; Sin, 2010). The majority of phenemographical studies do not involve the researcher participating in the educational process being investigated. Yet, as Richardson (1999) points out, "there is, in principle, no reason why phenomenographic research should not involve direct observation" (p. 58). In addition, as discussed in the current literature on teacher change resulting from collaboration, there is often a lack of direct observation of change in the classroom (Ballone-Duran et al., 2005; Clifford et al., 2008; Kane et al., 2002). To address this criticism, direct observations of the classroom instruction of the physics professor were conducted and used as complementary data to the interviews. The observations occurred in three setting: PHYS 7050, PHYS 1080, and PHYS 3000 (all detailed below). Additional data sources (Appendix C), including student interviews, survey instruments (Appendix H), and unobtrusive data (classroom documents) were collected to help crystallize the findings from the primary data (interviews) and complementary data (observations) (See Appendix E). Each of these is briefly described below.

Classroom observations.

Direct observation allows the researcher to be present in the here-and-now of an experience. Eisner (1991) states, “the richest vein of information is struck through direct observation of school and classroom life” (Eisner, 1991, p. 182). Observations provide knowledge about the context of a phenomenon and may allow the observer to see aspects of a phenomenon that participants are not aware of or are unwilling to discuss in an interview (Hoepfl, 1997; Patton, 1990). Therefore, classroom observations were an important complementary data source to the primary interview data in this study. All observed classes were audio recorded. In addition, the co-taught 7050 sessions were video recorded.

Observations of pre-service teacher classroom environment.

To fully observe the patterns in the teaching methods of the physics professor in PHYS 7050, I observed the full cycle of instruction over the entire summer semester (n=11 classes observed). This ensured that instruction in the beginning, the middle, and the end of the PHYS 7050 was observed to document any changes within the course. This time period allowed what Lincoln and Guba (1985) term ‘persistent observation’. Persistent observation’s focus “is to identify those characteristics and elements in the situation that are most relevant to the problem or issue being pursued and focusing on them in detail” (p. 304). While observing, I was “explicitly and self-consciously attending to the events and people” in the context I was researching (Dewalt & Dewalt, 2002, p. 68). My observations’ descriptive field notes were drawn up and focused on providing rich data on the account of particular events, depiction of events, observer’s behavior, reconstruction of dialogue, informal interactions, description of the physical setting, as well as emergent information (Bogdan & Biklen, 2006; Eisner, 1991; Patton, 1990).

The practice teaching component of PHYS 7050 in the undergraduate studio physics course (PHYS 1080) was observed as well throughout the summer. These provided a context for the instruction and discussion within PHYS 7050. Only the discussions following these sessions in PHYS 1080 were recorded.

Observations of alternative classroom environments.

To help assess the extent of the transformation in the physics professor's conceptions and practices in teaching for conceptual change along with the consistency of his statements concerning these, follow-up observations were made of the physics professor's teaching in a core physics course taught to physics majors who were not pre-service teachers. This course, PHYS 3000, was an upper-level lab course for physics majors. PHYS 3000 was chosen as it was the sole physics-related course taught by the physics professor in the following fall semester.

Observing in a course not designed for pre-service teachers provided the opportunity to further define how context dependent were the physics professor's conceptions and practices of teaching for conceptual change. Being a lab course placed inherent limits on the carryover. The focus of the lab course on students' investigations, designed to develop them into competent experimental researchers, varied significantly from the focus of PHYS 7050. Traditionally taught and approached differently than physics content classes, lab courses center on students performing investigations. These limitations, while noted, were unavoidable due to the constraints of the physics professor's schedule.

Two PHYS 3000 classes were observed in the middle of the course. Both observed classes involved the physics professor previewing and providing background for several upcoming student-performed physics experiments. This context allowed the physics professor's pedagogy, focused on students' ideas and misconceptions concerning the underlying physics of the experiments, to be examined.

An open-ended interview was conducted with the physics professor following the observation of the two PHYS 3000 classes. The focus of this interview was the physics professor's perspective on his teaching for conceptual change in the PHYS 3000 class. His views on the applicability of teaching for conceptual change in physics major classes were probed and significant observations from the PHYS 3000 class were presented for his interpretation and explanation (See Appendix D).

Observational Tools.

In observing a research environment, as with a camera, there must be a focus. My focus centered on the conceptions and practices of a physics professor's teaching for conceptual change (Dewalt & Dewalt, 2002; Patton, 1990). While it is impossible to map out all the observations in advance, since many emerge from a growing familiarity with the observed environment (Lee, 1970), several tools were used to provide a framework within which to observe. Observational tools utilized are described below.

Observational protocol.

An observational protocol or 'sensitizing concepts' was used to provide a basic framework to focus and organize my observations (Creswell, 2003; Patton, 1990). The Reformed Teaching Observation Protocol (RTOP) is a widely-used instrument developed by the Evaluation Facilitation Group, Arizona Collaborative for Excellence in the Preparation of Teachers (ACEPT) at Arizona State University. It was designed as a classroom-based observation and assessment tool to evaluate the extent of reformed teaching present in science and mathematics classrooms. Widely established as the principle instrument for assessing reform teaching in K-12 classrooms (Sawada et al., 2002), it has likewise been adopted to assess reform teaching in higher-education classrooms (Ellett, Monsaas, Martin-Hansen, & Demir, 2012; Lawson et al., 2002) and has been shown to correlate with a teacher's PCK (Park & Chen, 2012). With the RTOP's emphasis on reformed teaching encompassing active student learning, eliciting and valuing students' preconceptions, and collaborative learning (MacIsaac & Falconer, 2002; Piburn et al., 2000), it provided a well-established instrument for observing attributes of teaching for conceptual change present in the classroom.

The Annotated RTOP (See Appendix F) is a modification of the RTOP by Ellett (2009) designed to reduce error in measurement and further enhance rater agreement. Both the RTOP and annotated RTOP are designed to be used by trained observers. In preparation for utilizing the annotated RTOP, I attended a two-day workshop led by a certified expert. This workshop included large group discussions on each indicator, followed by classroom observations and a comparison and calibration of my rating to other raters facilitated by an expert trainer. I specifically conducted an RTOP evaluation of several PHYS 7050 classes as well as the PHYS 3000 class. Being a trained observer, I utilized the annotated RTOP with its correlation to key attributes of teaching for conceptual change as my observation protocol.

Field notes.

Along with the RTOP instrument and direct descriptive field notes from my observations, I recorded reflective field notes. These field notes helped document my subjective journey through my research. They included my reactions, speculations, impressions of my research along with clarification and corrections of mistakes or misunderstandings in my field notes. Specific areas included reflections on my research analysis, research methods, ethical conflicts, and personal biases (Bogdan & Biklen, 2006).

Video and audio recordings.

The instruction by the physics professor was either audiotaped or videotaped in PHYS 7050. All observed classes were audio recorded. PHYS 7050 co-taught sessions were also video recorded. The focus of both recordings was solely on the instructor. The recordings were used to substantiate the descriptive field notes and directly analyze the pedagogical methods implemented in the class.

CBAM instrumentation.

To help measure the change of the physics professor, a CBAM instrument, focusing on the evolving of an individual's thinking (stages of concern) (Hord et al., 1987), was used.

Stages of Concern Questionnaire (SoCQ).

The SoCQ was administered to the physics professor near the beginning and the end of the course to gauge his progression in the use of the innovation – teaching for conceptual change. The physics professor's concern profile (Appendix G), based on seven levels of progression, was generated corresponding to the beginning and ending of the process (Hall et al., 1998).

MAT student data.

An important secondary data source for this study was the MAT students. While this study did not focus on the changes in their views of teaching for conceptual change as described in the preliminary study (Stoll et al., 2014), collecting data on their perceptions (interviews), understanding (survey instruments), and behavior (observations) provided important supporting data. This data documented the variations of teaching for conceptual change experienced by the MAT students. This data helped reveal, confirm, and further explain the key findings, which emerged from the interviews and observations of the physics professor concerning teaching for conceptual change and how it was interpreted by the learners. Below is a brief overview of this emergent data collected from the MAT students.

MAT student interviews.

The selected MAT students (n=4) were interviewed twice in a semi-structured responsive interview (20-30 minutes). The first interviews solicited students' educational and teaching background, their perspectives on their teaching and learning practices, and their expectations for PHYS 7050 (See Appendix D). These interviews were conducted at the beginning of the summer session of PHYS 7050.

The second interviews occurred at end of the summer semester and focused on students' perceived changes in their views of teaching and learning based on their experience in PHYS 7050 (See Appendix D). The specific aspects of the course, which the students associate with helping to change their views, were solicited. The focal point of these interviews was to find out the variations in the students' learning experiences in PHYS 7050 (Holmqvist et al., 2008) and to provide elaboration and confirmation of the learning process in PHYS 7050, as identified by the students. Both of which were used primarily to triangulate with the physics professor's interview data.

Survey instruments.

Two survey instruments, the Force Concept Inventory (FCI) test and a Teaching Strategies survey, were utilized to assess the MAT students' learning of physics concepts and pedagogical understanding of teaching physics from a conceptual change perspective, respectively. Both survey instruments were administered pre- and post- course and were part of the course design. These instruments provided secondary quantitative and qualitative data to help support the primary qualitative analysis (Eisner, 1991; Strauss & Corbin, 1990). Both instruments focused on measuring change, allowing a comparison of students' conceptual knowledge and pedagogical knowledge before and after PHYS 7050. While they were able to help quantify this change, the instruments were limited in their ability to explain and provide understanding of why and how the change took place.

Force Concept Inventory (FCI) test.

The FCI (Hestenes, Wells, & Swackhamer, 1992) is the most widely used test available to evaluate the effectiveness of instruction in introductory physics courses, acknowledged even by its critics (Hake, 1998; Huffman & Heller, 1995). The FCI tests six conceptual dimensions of Newtonian force theory and students' misconceptions associated with these. Hake (1998), based on over 6000 FCI student results, defined the average normalized gain (g) from the FCI as an effective measure of the conceptual understanding promoted by a course using the following ranges: high ($g \geq 0.7$), medium ($0.7 > g \geq 0.3$), and low ($g < 0.3$).

Teaching Strategies Survey instrument.

The Teaching Strategies Survey instrument (See Appendix H) is primarily a qualitative measure designed to elicit teachers' views on appropriate practices regarding how to respond to students' ideas which differ from those of science. It utilizes a series of open-ended questions that initially focus on general beliefs, regarding effective approaches for addressing such ideas and ends with a specific scenario from an actual physics classroom to provide insight into how those beliefs and approaches would be enacted (Stoll et al., 2012). Both the physics professor and the MAT students took this instrument at the beginning and end of the PHYS 7050 course.

Unobtrusive data.

The final collected data source was unobtrusive data. Unobtrusive data is not filtered through the observed participants, meaning it is unaffected by their observations, interpretations or biases (Hatch, 2002; Patton, 1990). This data included the course syllabus, copies of assignments, and other documents from PHYS 7050 that allowed me to analyze the teaching and learning of the course without interfering with the experience of participants during the enactment of the phenomenon being investigated.

Data Analysis

Qualitative data analysis involves working with the collected data to organize it, breaking it into manageable units, coding it, synthesizing it, and searching it for patterns (Bogdan & Biklen, 2006; Patton, 1990). In phenomenography, the purpose of analysis is developing categories of descriptions, representing different ways of understanding a phenomenon (Akerlind, 2012; Dahlgren, 1997; Hasselgren & Beach, 1997). This type of analysis is "necessarily iterative, and concepts and categories evolve gradually, as their meanings become clearer" (Entwistle, 1997, p. 21). Marton and Saljo (1997) describe the process as first a selection process that identifies the comments from interviews related to the phenomenon being studied. These comments are then sorted into groups, based on similarities and separated from other groups by differences. From the grouped comments, a core meaning for the group is extracted forming the categories. Borderline cases are used to help define the boundaries between the categories.

Iterative Analysis

Consistent with this methodology, I applied an iterative analysis process to my data (Figure 6). First, the audio recordings of the interviews were transcribed. Transcribed interviews were rechecked against the original audio files to ensure accuracy as they were the basis for the analysis (Collier-Reed & Ingerman, 2013). Initially, passages of the transcripts, where the physics professor reflected on teaching for conceptual change phenomena, were marked. These passages, identified from all relevant interviews, were collated together using NVivo, a qualitative analysis software. This "pool of meaning" then became the starting point for further analysis (Marton, 1994, p. 4428). The analysis' focus was the categories that emerged from the physics professor's awareness of key aspects of the phenomenon of teaching for conceptual change (Collier-Reed & Ingerman, 2013). My focus was "to bracket preconceived ideas", maintaining the focus on how the physics professor interpreted the teaching for conceptual change phenomenon (Marton, 1994). This analysis involved repeatedly reading the pool of related interviews' excerpts, probing for underlying areas of concentration and the intentionality behind them. The interviews' excerpts were then divided into related areas or categories. These categories were continually compared and contrasted to distinguish both similarities and differences. Key structural relationships were delineated in this manner showing both connections and differences between the categories. Distinctive categories emerged from the differentiating of key meanings and the delineation of the variations between them. These findings were rechecked against the original transcripts, refining each in a continual iterative process and maintaining a sense of the individual context (Akerlind, 2012).

The emergent categories were utilized in the integration of the class observation field notes with the recordings of PHYS 7050. Relevant points were noted in the field notes and the recordings of those section of the class were transcribed and indexed into the field notes, producing a set of integrated observation notes. These integrated notes were then coded and added to the collated "pool of meaning" excerpts from the interview data. These expanded "pool of meaning" collections were utilized in the continual refinement of the categories. This process enhanced the defining of the emergent categories, adding the dimension of the physics professor's practice of teaching for conceptual change. Capturing this through the recorded words of the physics professor in the context of his practice maintained the integrity of the phenomenographic methodology.

The emergent categories from this process were used as a framework to establish the change timeline of the physics professor's conceptions and practice of teaching for conceptual change during and beyond the collaboration. Both the interview and observation data were reexamined for evidence of the physics professor's change process, categorized by the research study's related questions on the physics professor's perspective on teaching for conceptual change as: 1) changes in the professor's conceptions, 2) changes in the professor's practices, and 3) learning environment factors identified by the professor that facilitated or hindered his change.

The evidence and insights that emerged through this process were crystallized by comparing the findings with the secondary data sources (e.g., CBAM, MAT student interviews, student surveys, and class artifacts)(N. K. Denzin, 1989). This crystallization, along with peer debriefing, member checking, and negative cases (Lincoln & Guba, 1985; L. Richardson, 2000), were specific steps taken to establish the trustworthiness of the analysis and results (Bogdan & Biklen, 2006; Hoepfl, 1997; Patton, 1990). All are detailed below and represented in Figure 6.

Crystallization

Crystallization is a postmodern method of combining multiple forms of analysis and genres of representation in an immersive process to produce an account of a phenomenon. It extends beyond the traditional triangulation which draws on multiple sources of evidence from different data sources to establish "converging lines of inquiry" (Yin, 2009, p. 115). "Crystallization provides us with a deepened, complex, thoroughly partial, understanding of the topic" (L. Richardson, 2000, p. 934). Crystallization does not involve a set pattern, but an immersive environment, where the iterative process of data processing and looking at the phenomenon through multiple means intuitively develops into reportable findings (Borkan, 1999). To crystallize my claims, multiple data sources were drawn upon in an iterative, immersive process (See Figure 6 and Appendix E). Following the emerging and defining of the phenomenon's categories from the interview data, the classroom field notes, embedded with indexed classroom audio transcript excerpts, were coded. Using the defined category codes, this analysis focused on the practice of the physics professor as recorded through observation and his recorded word. This analysis provided another iteration in the defining and contextualizing of the categories.

Peer Debriefing

Defined by Lincoln and Gupa (1985) as "exposing oneself to a disinterested peer" (p. 308), peer debriefing was a technique used to make aspects of my inquiry more explicit. My peer debriefer was a fellow graduate student in science education and a veteran high school physics teacher. His experience uniquely qualified him as a knowledgeable critic, understanding both the theory of conceptual change and the experience of teaching physics. We already had an established mutual respect based on a longstanding working relationship (Spall, 1998).

Our peer debriefing sessions began at the beginning of my analysis and continued into the writing of my dissertation. These sessions presented a forum to test hypothesis, to test new steps in my emerging methodological design, and an opportunity for catharsis by expressing emotions and feeling which may have been clouding my judgment (Creswell, 2003; Lincoln & Guba, 1985; Spall, 1998). The peer debriefer, through his questions and probing, helped keep me honest in identifying my biases, clarifying my interpretations, and more deeply exploring meanings. One example of the peer debriefing process was in the early categorizing of my data. I separated similar interview excerpts into different groupings and labeled them with very basic descriptors, e.g. didactic teaching, effective teaching, students' ideas, students' framework, conceptual framework, and modeling. Prior to our meeting, my peer debriefer reviewed my collection of interview excerpts. At the meeting we discussed the categories. My peer reviewer challenged me on the basic descriptors and pushed me toward more traditional teaching descriptors. In response, I revised my categories to transactional teaching, active teaching, focus on teaching, students' ideas, students' learning, framework, conceptual change, and modeling. While these categories continued to evolve, this was an important step in the process.

Member Check

Member checking was used throughout the research process. The accuracy of my interpreted summary of the physics professor's experience was checked by providing opportunities for the physics professor to provide feedback on the accuracy of the interpretation (Creswell, 2003). Within the iterative process of data collection and analysis, subsequent interviews were used to solicit feedback on the accuracy of my interpretations of the physics professor's experiences from earlier interviews. Following the completion of my findings chapter, the physics professor reviewed them and we met to discuss them. The feedback received through this member checking was used to help refine, to improve the accuracy, and to better clarify my findings.

Negative Cases

In the iterative process of data analysis, negative cases or trends that run counter to the identified themes emerged. While this reflected the complexity of real life, it provided the opportunity to test my working hypothesis and refine my conclusions to include all known cases. This process increased my understanding of the identified themes (Creswell, 2003; Patton, 1990). An example was the observed pattern of direct instruction in PHYS 3000 during the extended practice period. This sharp contrast with the pattern of instruction observed in PHYS 7050 required a closer look at how the context of the class influenced the physics professor's practice.

Role of the Researcher

In qualitative research, the researcher's focus on understanding the phenomenon under investigation in its natural context requires the researcher to develop a closeness of both physical proximity and a social sense of intimacy and confidentiality with his or her subjects (Patton, 1990). The researcher serves as 'a human instrument', being the primary means whereby data is collected and interpreted (Hoepfl, 1997). Just like the sensitivity of instruments is essential in making precise measurements, researchers need to exhibit 'theoretical sensitivity'. "Theoretical sensitivity refers to the attribute of having insight, the ability to give meaning to data, the capacity to understand, and capability to separate the pertinent from that which isn't" (Strauss & Corbin, 1990, p. 42). Phenomenography requires a refined theoretical sensitivity where the researcher is to 'bracket preconceived ideas.' Instead of comparing how responses reflect the researcher's understanding of the phenomena, the focus shifts to the similarities and differences in the way the phenomenon appears to the participants (Marton, 1994). This interaction of the researcher with the context and participants, plus the influence it has on the research, must be acknowledged. Below I acknowledge and discuss my biases, values, and personal interests surrounding my research topic and process (Creswell, 2003, p. 21).

My researcher's role was as a participant observer, collecting data in the naturalistic setting of my researched phenomenon by observing and taking part in the activities of the people studied (Dewalt & Dewalt, 2002). As Merriam (1998) notes, "the researcher's observer activities are known to the group; participation in the group is definitely secondary to the role of information gathered" (p. 101). To accomplish this, I engaged in a prolonged observation of the physics professor's teaching over the course of a summer semester and in additional courses in the fall semester. Since my research focused on the physics professor's experience, it was imperative that I establish a relationship built on trust and a solid rapport with him. While my primary role was observing and gathering information, I did at times actively participate in the class. My participation occurred in response to an initiation by the physics professor and was clearly delineated in both classroom observation notes and the recorded audio transcripts of the class. From the beginning, I clearly outlined my responsibilities as a researcher and the responsibilities of the participants in my consent form (Appendix A). Throughout my research, I focused on building and maintaining the trust of my participants. This included being up-front about my expectations, restricting my activities to those agreed upon, and seeking feedback along the way on my interpretations from the participants (member checks). In my data collection, I endeavored to make the observational data as close a representation to the actual events as possible by reviewing it, comparing it with other data such as video and audio recordings, and seeking feedback from others present. In addition, my field notes and analysis included notes and memos on my personal reflections, marking my own process in a transparent manner throughout the research process.

Limitations of the Study

The focus of this section is to acknowledge limitations of the study and detail how these limitations were minimized throughout the study. Qualitative research embraces a criterion of validity typically referred to as trustworthiness which is used in determining how accurate the findings are from the perspective of the researcher, the participant, or the readers (Creswell, 2003). Lincoln and Guba (1985) defined trustworthiness for qualitative research with the set of criteria of credibility, transferability, dependability and confirmability. Each of these is now discussed concerning their meaning and how they were established in my research study. Table 2 lists each of these criteria and what data sources and analysis techniques support them.

Table 2

Trustworthy Criteria for the Study

Credibility	Transferability	Dependability	Confirmability
Purposeful Selection	Thick Description	Crystallization	Data Reduction Charts
Prolonged Engagement	Purposeful Selection	Reflective Field Notes	Research Log
Persistent Observation	Multiple Data Sources	Member Check	Direct Excerpts
Crystallization		Negative Case Studies	Peer Debriefing
Member Checking		Rich Description of Methodology	Supporting Research Literature
Peer Debriefing			
Negative Studies			

Credibility

Credibility relates to how well the constructed realities of the participants align with the representation of those realities presented by the researcher. This criterion corresponds with the traditional internal validity in quantitative research. Lincoln and Guba (1985) maintain that in establishing credibility it helps to ensure the other three aspects of trustworthiness. My discussion focuses primarily on establishing the credibility of my study. For this I utilized the techniques of purposeful sampling, prolonged engagement, persistent observation, crystallization, peer debriefing, member checking, and negative studies.

Transferability

In Lincoln and Guba's (1985) trustworthiness criteria, transferability relates to external validity or generalizability. Transferability is the amount to which the findings can be transferred to other settings or groups (Graneheim & Lundman, 2004). The degree of transferability is not a claim the researcher can make due to its dependence on the context of the study. Instead, it is for the reader to determine the amount of transferability that exists between the presented study and other cases. The researcher focuses on providing a 'thick description' of the research study which will allow the reader to determine the amount of transferability (Lincoln & Guba, 1985).

> Thick description refers to the researcher's task of both describing and interpreting observed social action (or behavior) within its particular context….Thick description accurately describes observed social actions and assigns purpose and intentionality to these actions, by way of the researcher's understanding and clear description of the context under which the social actions took place. Thick description captures the thoughts and feelings of participants as well as the often complex web of relationships among them. Thick description leads to thick interpretation, which in turns leads to thick meaning of the research findings for the researchers and participants themselves, and for the report's intended readership. (Ponterotto, 2006, p. 543)

In order to present a 'thick description', I incorporated a rich and detailed account of my analysis and interpretation, drawing on an extensive data collection. To help develop the "thick description" my research study utilized a purposeful sampling of its participants and multiple data sources (Appendix E).

Dependability

Dependability corresponds with reliability and focuses on the researcher's process of inquiry and how logical, traceable, and documented it is. To ensure the consistency in my research results, I used crystallization, reflection on my research process in my field notes, members check, and reevaluation of my research process with negative case studies.

Furthermore, I provided a rich and detailed description of my research design including the processes for selection of participants, interviews, classroom observation, and analysis methods.

Confirmability

Confirmability is established by the researcher, providing necessary evidence to show that the results are logical in regards to the context, time, and data collection. Lincoln and Gupta (1985) recommend establishing an audit trail to help establish confirmability. Data reduction charts were constructed in the coding and interpretation process as well as my log of the research process are presented in Appendix I to help establish this auditable trail. Direct excerpts from the raw data were utilized to support my interpretations and conclusions (Appendix J). References from other research literature with findings which support my interpretations were also cited.

One persistent challenge in conducting phenomenographical, qualitative research is the bracketing of the researcher's preconceived ideas. Instead of considering how responses to the examined phenomenon compare to my understanding of the phenomenon, it is necessary to focus on the similarities and differences found in how the participants interpret and experience the phenomenon. Being cognizant of this helped me consciously evaluate my analysis and interpretations for this tendency. In addition, the consistent and prevalent use of member checks and peer debriefing helped ensure that my research findings aligned with the central goal - clearly presenting the categorized experiences of the phenomenon of teacher change resulting from collaboration from the perspective of the experienced. The significance of this research and its findings are discussed next.

Significance of Study

The key, I believe, to reforming physics education lies with physics teachers, and at the core of this is the physics professor's teaching of introductory physics. Traditional introductory physics courses are strong deterrents for prospective physics majors and physics teachers alike. Teaching practices are inextricably linked to teaching conceptions, requiring a powerful stimulus and a complex process to change. In theory, such a change mechanism is the frequently proposed collaborations between College of Science faculty and College of Education faculty. The change process involved with physics faculty members in these collaborations needs to be more fully explored. My study's aim centers on bringing insight into this gap in the literature. Understanding the change process within a physics professor, during and beyond such a collaboration, will allow the design of more effective collaborative PD. This will help improve physics instruction, especially at the introductory level, which could curb the current "brain drain" of talented students, turned off to a future involving physics. As future physicists and physics teachers are effectively taught, this influence will spread reforms in physics education both in size and scope.

4 FINDINGS

Introduction

The conceptualization and practice of teaching for conceptual change of a physics professor are presented and discussed in this chapter. The chapter is structured around a case study of a physics professor engaged in collaboratively teaching with a science education professor a physics course for future science teachers. Specific evidence is presented to answer my research question: How is teaching for conceptual change conceptualized and practiced by a physics professor during and beyond an extended collaboration with a science education professor focused on teaching for conceptual change and its related sub-questions:

1. What is the evidence of change in a physics professor's conceptions of teaching for conceptual change?
2. What is the evidence of change in a physics professor's practices of teaching for conceptual change?
3. What are the learning-environment characteristics identified by the physics professor that either facilitated or hindered changes in his conceptions and/or practices in teaching for conceptual change?

The chapter is organized by first presenting a background sketch of the physics professor, followed by different categories of conceptions of teaching that emerged from the professor's description and observed practice. Evidence of change within these categories is presented, followed by the facilitators and constraints to these changes.

In this section, a *conception* was viewed from a conceptual change perspective as a concept (idea) that played a generative or organizing role in thought marked by internal complexity and plurality (Strike & Posner, 1992). Students' initial ideas were referenced as *preconceptions* and not as *misconceptions*. *Misconceptions* connote that the ideas are wrong and must be replaced, something not supported in more recent conceptual change literature (J. Smith et al., 1993). The exception was whenever the physics professor used the term *misconception*. It was included to accurately reflect his communicated ideas.

Physics Professor's Profile

The particularistic focus of this study was the teacher change of a single physics faculty member resulting from a unique collaboration with a science education professor in the specific area of teaching for conceptual case. This focus was both unique and revelatory requiring a single case study (Yin, 2009). This section presents the unique relevancy that Professor Fairbanks (pseudonym) embodies in his background and experience with regard to this study.

Professor Fairbanks was a tenured, associate physics professor at a large, southeastern Tier 1 research university. He held several leadership roles within the physics department and was actively engaged in both physics education and physics education research. He had fostered collaborative relationships focusing on physics education both within his department and out, notably with the College of Education. Recently, he helped lead the effort for his university to successfully secure a large grant to improve and promote the education of future physics teachers.

To appreciate the characteristics and distinctiveness of Professor Fairbanks collaboration with a science education professor in PHYS 7050, his personal and professional journey was examined with specific attention given to his educational teaching experience, research, and collaboration history.

Educational History

Professor Fairbanks joined the department several decades ago following a PhD from an ivy-league school and a post-doc in a government lab. At the time of his hiring, he joined a very senior department. He explained, “There was a twenty-year gap where they hadn’t hired any physics people or nobody who had stayed…the department on the physics side was really pretty set in their ways. So, I was at that point on my own to do stuff” (Interview, June 10, 2013).

Teaching History

One of his first duties was teaching introductory physics classes. His prior teaching experience consisted solely of having taught labs and recitation sections as a graduate student. The preparation provided for his teaching was “basically being handed the textbook and maybe someone else’s syllabus, saying, ‘have a nice time’” (Interview, June 10, 2013). He described it as learning by trial-and-error. “Mimicking what I had seen before and getting in there and doing it with little preparation,” said Fairbanks (Interview, June 10, 2013). At that time, he lacked the experience and feedback to evaluate the effectiveness of his teaching as he stated, “I don’t really have that much of a sense of whether I did, a good job or a bad job, and I had really no way to gauge that.” (Interview June 10, 2013).

Despite this challenging beginning, Professor Fairbanks cared about teaching and was interested in improving. During his second year, his department chair nominated and encouraged him to attend a new faculty workshop sponsored by the American Physical Society (APS). At the workshop, new physics faculty members were exposed to physics education research with the leading researchers in the field presenting findings. As Fairbanks recalled, “The big names - McDermott and Beichner and Priscilla Laws…were there” (Interview, June 10, 2013). Professor Fairbanks immediately started applying what he learned. He elaborated, “I came back after learning all these great things; wanted to do them right away. And so I told my class about what I had learned, and I started putting in some peer instruction stuff right away" (Interview, June 10, 2013). However, many of his students resented the change. Fairbanks explained, "At the end of the semester I got all these comments in the students' evaluations that said, 'I liked the new things that he brought to the class the second half, but he shouldn't have changed'" (Interview, June 10, 2013). His department was indifferent to the teaching changes he wanted to implement. He shared, "I gave a department colloquium about stuff I'd heard about, which, generally, nobody cared about. Nobody was interested at all in that, at that point" (Interview, June 10, 2013).

Despite his isolation, Professor Fairbanks continued to integrate many of the new methods into his classes. He reflected, "I started using that on my own more…peer instruction was the stuff that could easily be brought in as a *lone wolf* [emphasis added]" (Interview, June 10, 2013). The motivation was a personal responsibility he felt for his students. He asserted,

> Once you get convinced…the way you started doing things, and the way you naturally want to do them because it's what I've seen before, is not very effective. And then you see the results you're getting. You've got to back up, because that's not very effective, and that there are other things that might be more effective….I'd say it was a moral question. It's just not possible to go back and say, oh, just give that up and teach the way I like the best, if that's not most effective. (Interview, June 10, 2013)

He advanced to the position of undergrad director and to teaching more upper division courses. He was able to interact with students in other positive ways, which gave him a reprieve from focusing on interactive teaching in introductory courses. He recalled,

> So that was a relief in some ways, because it was very hard to be trying to do something

> different in the introductory-level lecture classes, and being on your own trying to do that, where you've got no feedback or no help from other people as to figuring out what was working and what didn't work. (Interview, June 10, 2013)

In the upper division courses, the class sizes were smaller and more highly motivated and the instructor was always on his own to design and implement the course. Professor Fairbanks continued to carry over some of what he was doing without the pressure and challenge. Key ideas Professor Fairbanks carried over into these courses he identified as:

> Really seek to understand where the students are when you start, instead of assuming that they are at a certain point; assuming that they are going to have misconceptions and that, they're going to have struggles, and having tried to identify them along the way as opposed to just presenting material, and assuming…if they work hard enough they'll understand it. (Interview, June 10, 2013)

Research History

Professor Fairbanks' primary research was in the interdisciplinary field of condensed matter. While Professor Fairbanks was aware of research being done in physics education, this was not his focus. He stated,

> I saw…there were people who were doing research in these areas…it certainly wasn't something I was going to pursue myself very much or to a point of trying to actually make it a research area. (Interview, June 10, 2013)

By continuing to attend APS meetings, he became more exposed to education research, aware of current developments in the physics education field, and connected within the community of Physics Education Research (PER). Eventually, his involvement increased. He recalled, "I did, at times, later on, give some talks at those meetings, more education-related talks, related to lab reform or various other things like that" (Interview, June 10, 2013).

A key event in Professor Fairbanks increased involvement with education research at his university was the hiring of a PER faculty member by the physics department. He recalled,

> So it was really the hiring of Dr. Nora [pseudonym] that changed things, because now I bring in somebody who - there was an expectation that there was going to be some educational research. And so there was an opportunity to be a part of that without having to go and figure out how to do it all by myself. So that's what encouraged me to get involved. (Interview, June 10, 2013)

Along with the hiring of the PER faculty member came the introduction of a reformed model studio classroom for introductory physics (Beichner, 2008). As the undergraduate director, Professor Fairbanks was directly involved in the decision making. Research-type questions naturally arose from these decisions. Fairbanks explained, "You have questions: Okay, how are we going to assess what we're doing, and with the expectation that we were going to publish" (Interview, June 10, 2013). With the collaboration, Professor Fairbanks realized that if he wanted to continue the work he needed to take more on himself utilizing, resources available in the field. At this time he was experiencing a changing attitude toward his science research. Professor Fairbanks elaborated,

> My other research area, [condensed matter] was not getting outside funding…over time, becoming less enthusiastic, I'd say, about that research. So those things all came together at the right time to help push me to be more serious about educational research. And there was internal money available. (Interview, June 10, 2013)

There was the success of being involved with several mini-grants, focused on revising upper division labs and introductory physics classes. This led to talks at conferences and a growing interest in attending American Association of Physics Teachers (AAPT) meetings to learn more about PER. Personally, he found this more rewarding than traditional physics research. He continued,

> For me it seems important. I can see it maybe more directly, that what we're learning can have a lot of positive impact on people. When you're doing something in condensed matter physics…sometimes you wonder whether you get a paper out, whether anybody actually reads it or learns anything from…or you're just producing a lot of papers….But I think it's the interaction with the students…that's drawn me into educational research…and drew me into the role of undergraduate director– is just an interest in the students, and how can we do the best by them and help them to get as far and be in as good a position as we can. (Interview, June 10, 2013)

Collaboration History

In Professor Fairbanks' role as undergraduate director, he focused on changing the undergraduate program by improving classes and creating new classes. One of his major efforts was to develop a Bachelors in Science (BS) degree in physics with an education concentration. This program involved collaborating with the College of Education. Fairbanks stated, "It takes a lot of working out and in fact, we co-advise the students that are in that program…that helped to lead to this other [PHYS 7050 collaboration]….Because there were already connections between the departments" (Interview, June 12, 2013). The PHYS 7050 collaboration, as detailed earlier, arose from a need to provide additional physics-content instruction for teacher candidates in the MAT secondary science program seeking a broad-field science certification. Professor

Fairbanks, as undergraduate director, recognized the need for change and had a desire to take advantage of exposing these students to physics teaching's best practices. He explained,

> As the undergraduate director, it also fell to me– the students in the MAT program who needed physics classes to get them matched up with the right class….Got to recognize that we really didn't have the right kind of classes. Since our studio physics had developed and so along the way a lot more understanding of physics teaching best practices and other ways to do things, so it seemed natural to take advantage of that as well in the teacher practices….We had the studio class, which we could use and take advantage of to put those things together. (Interview, June 10, 2013)

MAT students started observing the undergraduate studio classes. Even with this exposure, Professor Fairbanks recognized the limitations of what the physics department could offer the MAT students. On his own initiative, he started meeting with the students outside of the undergraduate classes. He began to identify more of what was needed; also, how little he knew about the rest of the MAT students' teacher preparation experience; and the need for further assistance. Reflecting back, Professor Fairbanks explained,

> In developing a classroom, although it's a physics class, we recognize that we don't know that much about what the MAT students see in their other classes. We don't have that much experience in what they really need, and so that we want to involve the College of Education as much and in every way that we can because it's going to be for the benefit of the students. (Interview, June 5, 2012)

Out of this need developed PHYS 7050 where MAT students were co-taught physics content and instruction by Professor Fairbanks and conceptual change focused pedagogy by Professor Crefeld, a science education professor from the College of Education. At the outset of the first co-teaching of PHYS 7050, Professor Fairbanks envisioned several areas of impact the collaboration would have on both his department and himself. He speculated on the broad effect stating,

> I think one thing that all those things change and hopefully change beyond me and the department is the view of physics teaching as a high-quality pathway for physics majors….Bringing more respect to that within the physics community and thinking about that, then, as we teach our classes for physics majors … because it changes then how you think about what you're doing because you're not just teaching them physics but you're modeling teaching. (Interview, June 5, 2012)

He continued by discussing the effect it would have on his teaching. Fairbanks elaborated,

> I'm going to be learning more of the theory side of things. Just being exposed to more of the conceptual change, and so it will give me more tools also to help understand how to bring about conceptual change in my students at all levels of the class. (Interview, June 5, 2012)

As seen in Professor Fairbanks' profile and words, he was a highly motivated instructor with a deep interest in students' success. His personal journey to this collaboration from a "lone wolf" practitioner to an influential leader and educational researcher in the physics department was unique. With this background, Professor Fairbanks' conceptions of teaching expressed through this PHYS 7050 collaboration are now examined.

Emergent Categories of Teaching for Conceptual Change

Teaching for conceptual change is defined by Hewson et al. (1998) as "teaching that explicitly aims to help students experience conceptual change learning, and meets guidelines consistent with the conceptual change model" (p. 200). Teaching for conceptual change was the pedagogical goal of the PHYS 7050 collaboration.

Five qualitatively different approaches to teaching for conceptual change emerged from the analysis of the physics professor's interviews (Table 3). These were a/an: a) transactional teaching approach; b) active teaching approach; c) students' ideas approach; d) students' learning approach; and e) conceptual change approach. While these categories represented distinctive views reflected by the faculty member, these also represented an increasing complexity of the understanding of conceptual change. Each new category grew in its sophistication of teaching for conceptual change, acknowledging the dimension found in the previous categories and further distinguishing additional aspects of the phenomena. A progression from teacher-centered to student-centered instruction was found along with a novice view to more expert view on students' ideas (Kember, 1997; Prosser et al., 1994).

Each category is described in detail. Verbatim quotes were included from the relevant interviews to highlight key attributes of the category. The quotes were illustrative, not defining, as one single quote cannot capture all the defining characteristics of the category. The categories were not mutually exclusive, but instead represent a progression of ideas. The physics professor would often simultaneously express ideas that would fall within several different categories, showing a concurrence of ideas of different sophistication in both his conceptions and practices. Later this was discussed as part of the change process.

1. Transactional Teaching Approach

In this category, the physics professor's practice of teaching for conceptual change was the presentation of the material through direct instruction. The approach was teacher-focused as Professor Fairbanks used a lecture style to directly transmit the material to students. The underlying assumption was that students will not arrive at these ideas independently, but must be told, and if the students work hard enough they will understand. Professor Fairbanks expounded on this assumption, reflecting back on lessons he had learned from teaching introductory physics classes and carried with him into teaching upper level physics classes. One change was dismissing his earlier assumption, prominent among his peers that, “just presenting material, and assuming if they [students] work hard enough they’ll understand it” (Interview, June 10, 2013). Professor Fairbanks readily acknowledged that was not an ideal way of teaching. In his teaching, he proactively attempted to dissuade the students from teaching in this transactional or lecture style. Early in the course when leading a discussion about different learning styles, Professor Fairbanks expounded on the prevalence of lecture in physics teaching with the need to change. He stated,

> The lecture style doesn't work for everyone...the straight lecture style. And the ones that it does work for are those whom physics come more naturally to. Who go on to become physics professors who then go and teach in that same style, because it worked just great for them….That is the cycle that you get which we are trying to break. (Class 2 Observation, June 13, 2013)

As shown in his profile, lecture was the teaching model Professor Fairbanks experienced as a student and embraced at the beginning of his teaching. Just as he experienced, Professor Fairbanks recognized similar challenges students faced when they arrive with expectations that teaching should resemble what they experienced, but were now presented with a different model of teaching. He expressed this challenge as part of the conceptual change that took place in the students in how they view teaching. Describing it as a “messing up” of students’ ideas, students were presented with an environment in the SCALEUP classroom, where the table layout, the room construction, and the focus were not conducive with many students' initial ideas of teaching as "more didactic". Professor Fairbanks pointed out,

> And they're being told not to do that [teach didactically]. So they're…feeling at a lost at the beginning…and some of them want to fall back on standing at the board and teaching. Doing a little more direct instruction…And that's a hard thing for them to learn to do. Hard thing for me to learn to do. (Interview, July 10, 2013)

Professor Fairbanks acknowledged struggling with not reverting back to a transactional mode of teaching which he described as a "sage on the stage" delivery of direct instruction. This common pattern was found throughout my observing Professor Fairbanks. He began by questioning students and leading class discussions, but then transitioned into a lecture mode. Professor Fairbanks admitted this statement was true, especially in areas where he was quite familiar with the topic and had abundant information to cover. One area when this repeatedly occurred was sharing common students' preconceptions of physics concepts. His instructions in these instances, he self-described as, "get into a laundry list of things that the students may do…on the material itself, get into more expert mode" (Interview, July 10, 2013).

A representative episode occurred in a discussion on forces and the representation of forces through free body diagrams (FBD). The instruction involved students individually working through several force examples and then volunteers coming to the board and drawing their responses on the board. After drawing his or her answer on the board, the student would explain it to the class. Professor Fairbanks proceeded to ask the student, then the rest of the class, what type of issues one might expect from students working through this example in his or her classroom. The students would soon be leading these exercises in the undergraduate class. The example, in question, involved a box at rest on an incline plane. In response to Professor

Fairbanks' question about other issues which might come up, students, Amy and Lynn (pseudonyms), responded that the magnitude of the normal force and the direction of the normal force could be an issue, respectively. Professor Fairbanks responded,

> The direction of the normal force and the direction of the weight...you will see a desire for them [students] to have it equal and opposite…Why do they make them opposite…it's Newton's 3rd Law. We haven't gotten to it yet, but they want to say it. (Class 4 Observation, June 20, 2013)

For the next four minutes of class, Professor Fairbanks continued by expounding on Newton's 3rd law, illustrating several classical issues students have in understanding it. After expressing all this information, he concluded with, "hopefully we don't run across it too much because they haven't gotten into Newton's 3rd law" (Class 4 Observation, June 20, 2013). Following this mini-lecture on a related but tangential issue, Professor Fairbanks acknowledged his reverting to direct instruction, but his desire was for the students to lead the instruction differently focusing on the expressed students' ideas. His tone was conciliatory as he conceded,

> I'm doing a lot of talking here and talking about issues, which are a little bigger than [what] we are doing. But I should shut up a lot more. Because when we get in there …you want them to do it and they have to get their ideas down and they then have to be confronted with issues within their own ideas. (Class 4 Observation, June 20, 2013)

The conflicting message between how Professor Fairbanks instructed the students to teach and how he modeled the instruction was pointed out by a student, George, who immediately responded, "That raises my next question. I have a sense that we are going to be leading the way you just led us" (Class 4 Observation, June 20, 2013). Professor Fairbanks responded, " And I am going to try from now on…do a better job of modeling what we are doing, but you are going to be facilitating" (Class 4 Observation, June 20, 2013).

Though still engaging in transactional teaching in practice, Professor Fairbanks actively advocated against transactional teaching. In discussing this change in his thinking, Professor Fairbanks identified transactional teaching's lack of effectiveness in students' learning as its key shortcoming and his motivator to develop different modes of teaching. He stated,

> The way you started doing things, and the way you naturally want to do them because it's what I've seen before, is not very effective. And then you see the results you're getting. You've got to back up, because that's not very effective, and that there are other things that might be more effective. (Interview, June 10, 2013)

2. Active Teaching Approach

This category focuses on teaching for conceptual change by engaging the student and using pedagogy designed by others and recognized as best practices in bringing about conceptual change. Professor Fairbanks' first exposure to this approach was during the fall of his second year as a professor at a new faculty workshop by the American Physical Society. The workshop's goal was, as stated by Professor Fairbanks, "to try to spread an understanding of what had been learned in the physics education research community and about effective teaching" (Interview, June 10, 2013). This exposure, combined with Professor Fairbanks' initial teaching results showing a lack of effectiveness in students' conceptual learning, compelled him to begin implementing research-based pedagogy and materials into his classes. As detailed in Professor Fairbanks profile, he began with changes in his classes which spread to a departmental-wide reform of the format of undergraduate physics classes. Eventually, there were changes in physics courses for future teachers, currently showcased in PHYS 7050.

Professor Fairbanks linked his changes in PHYS 7050 with a growing understanding of the research-based strategies for teaching physics. One initiative driving this change was his role as undergraduate director for the physics department as he needed to match up students in the MAT program with appropriate classes. He recognized a gap between what was being done for the undergraduate, but not the perspective teachers, and the logic of linking these two which developed into the PHYS 7050 class. He explained,

> Our studio physics had developed and so along the way a lot more understanding of physics teaching's best practices, and other ways to do things, so it seemed natural to take advantage of that as well in the teacher practices. (Interview, June 10, 2013)

Prior to the collaboration with the science education professor in PHYS 7050, Professor Fairbanks identified himself as familiar with "the research side of things and the pedagogies that have come out of the research-based instructional strategies" (Interview, June 5, 2012). Professor Fairbanks identified these strategies as "the upper level rules of what you should and shouldn't do" (Interview, July 23, 2012). The focus was in identifying typical students' preconceptions about a concept and specific strategies for teaching the concept. Professor Fairbanks' main source for this knowledge was in the literature of PER and its emphasis on concrete teaching methods to address students' preconceptions. As he stated, "These are things that the research shows….This is how we should do it and… here is a certain kind of activity that these people have developed to do this" (Interview, June 12, 2013).

The effectiveness of the pedagogy, Fairbanks asserted, was typically measured through assessments, which informed and shaped the teaching practices. Professor Fairbanks emphasized the FCI, as he expounded,

> It is the standard measurement accepted around the physics community. And it's a good

> measure of conceptual understanding of a segment of what's covering the course….It gives us some kind of a gauge of how we're doing as a department at teaching the content. (Interview, July 10, 2013)

Professor Fairbanks consistently administered a pre- and post- FCI to the PHYS 7050 students. His confidence in the assessment was evident in a marked change in his attitude toward the PHYS 7050 students' abilities following the initial results of the FCI. Addressing the class, Professor Fairbanks began,

> The diagnostic test on forces went very well. I was actually surprised, because I hadn't interacted that much on this and we struggled on the other things. So I wasn't very sure where we were, but you guys were actually in a pretty good place. (Class 4 Observation, June 20, 2013)

In the next interview, I followed up this observation of the change in his attitude toward the students' understanding by asking him if there were any changes in the way he approached the students as a result. Professor Fairbanks answered,

> The FCI scores at least gave me a point of comparison with last year. And I thought overall last year was pretty successful. So it gave me an indication that we should be able to be at least as successful. (Interview, July 10, 2013)

While these concrete methods discussed were intended to engage the students, the focus was still teacher-centered with the aim being what technique or method the teacher should implement to promote conceptual change on a specific concept. This category was different from the transactional teaching as students were engaged in active interactions with the teacher and each other in an active learning environment. Professor Fairbanks' definition of active learning environment was explained in his discussing the PHYS 7050 students' first experience of teaching in the undergraduate studio physics class. Professor Fairbanks posed the question, What makes the studio class an active learning environment? After several students responded, Professor Fairbanks expanded on their answers,

> They [students] are active because they are actually having to talk about...not just do the worksheet...it's not just all in their head as well. They are having to talk; they are asking questions. There is an interaction both with each other and with the instructor on a small scale basis. (Class 2 Observation, June 13, 2013)

A major limitation in this category, identified by Professor Fairbanks, was the lack of an underlying framework that explains why these strategies were effective. He explained,

> Knowing about the misconceptions and the recommended ways people approach them, but [I] didn't really have the underlying framework….It's like the Knight book [Physics 7050 textbook] which talks about the misconceptions and talks about the pedagogy of how he goes about it, but you don't know why exactly. (Interview, July 23, 2012)

Professor Fairbanks further elaborated, following the first summer of collaboration with the science education professor, juxtaposing his teaching in introductory physics classes influenced by physics education research and his observations of the science education professor teaching in PHYS 7050. He explained,

> In teaching an intro level class it was more understanding of what the literature said works and doesn't work from the physics education. And I realized…it is often looking at that what works and what doesn't work….It's usually not putting any overall framework onto that. It misses the psychology, education, cognitive studies all of that kind of stuff." (Interview, July 23, 2012)

He then contrasted that with the conceptual change approach he observed with the science education professor. He observed, “I think it gives a framework which has another way to evaluate…to think about the student’s experience which I think is more powerful than just the physics education research background by itself” (Interview, July 23, 2012).

Another limitation in this category is the specificity of the strategies, which limits their ability to be applied to other contexts or to extend the ideas to other classes. As Professor Fairbanks remarked, “All the things I’d learned were about intro classes….By the time I moved into upper division courses there was nobody talking about applying interactive techniques or anything like that in those types of classes” (Interview, June 12, 2013).

3. Students’ Ideas Approach

This category focused on eliciting students’ preconceptions of science phenomena. The expressed preconceptions serve as the starting point for teaching, focused on engaging these students’ ideas. From the first preliminary interview in discussing the role of students’ ideas in his teaching, Professor Fairbanks consistently expressed this concept. He explained,

> To know where the students are, having them doing things like exercises, where they reflect or where they do something on a whiteboard, where I have a way to determine what the ideas are that they have going in. So I can use that as the starting point and I can use that to know where we need to go. (Interview, June 5, 2012)

In an interview prior to the second year of the study, Professor Fairbanks again expressed this idea when asked, “How will you instruct the future teachers to approach students’ ideas?” Professor Fairbanks answered, “The students can’t change their ideas if they don’t know what they are, if they haven’t actually engaged the ideas that they have, and you can’t help with that if you don’t know what they are” (Interview, June 12, 2013).

The teaching, as advocated early on by Professor Fairbanks, while focused on students' expressed ideas, was teacher-focused. He emphasized the teacher's matching these students' ideas to a list of commonly known conceptions and developed pedagogical strategies designed to confront and change these ideas. In the initial interview, Professor Fairbanks identified this method in his teaching approach to students' initial ideas expressing,

> It's being aware of from the research side of what people have found to be common conceptions that the students have. And especially where they conflict with an expert construction of those ideas in that area. It's developing ways that try to understand where these students are in particular and helping them to understand where they are in particular. (Interview, June 10, 2012)

Creating a safe environment where students feel comfortable expressing their ideas was essential. Professor Fairbanks expressed this importance and sought to create such an environment. In his initial description of the goal of the class to the PHYS 7050 students, he explained the importance of an environment where students were comfortable sharing wrong answers. He stated,

> In the classroom we want to create an environment where students are willing to make mistakes. Because if they are afraid to answer, then their ideas, which may not be correct, will not come out. They never engage them. They never change. They have to be willing to make mistakes, have wrong answers. And so we need to undergo that in here. I want you all to be willing to make mistakes. (Class 1 Observation, June 10, 2013)

Along with recognizing that students were not blank slates and do come in with preconceived ideas, there was a respect and valuing of these students' ideas, recognizing these ideas had a personal experiential basis. Professor Fairbanks, identifying this at the very beginning of the first class, stated,

> They [students] come into a physics classroom for the first time and say I don't know any physics. I've never done any physics. Well, they've lived in the world for how many so years. No matter what they think, they come in with strong ideas of how things work. (Class 1 Observation, June 10, 2013)

In his initial interview, Professor Fairbanks further expounded on the experiential basis of students' ideas in discussing the role students' ideas play in their learning of physics. He shared,

> I try to communicate to the students, is that they come in with certain ideas for good reasons….So if they have an idea that things naturally just come to rest, it doesn't come out of nowhere. It actually comes out of their experience. So you're not just introducing a new idea. You're actually trying to get them to re-interpret their twenty-some-odd years of experience and see it and construct it in a new way. So it's vitally important with the ideas that they come in with and how they've put together their experiences into the ideas that they have. (Interview, June 5, 2012)

According to him, once these ideas were expressed, the focus became having the students compare their ideas of a phenomenon with the scientific ideas and creating a conflict that emphasized any differences. Fairbanks addressed this in several interviews, stating, "You get those ideas out there and they do something and…you force them to compare those on a particular topic" (Interview, July 21, 2013). The focus he asserted was to, "Recognize a conflict in what they thought would happen and how it fits with what really happens" (Interview, July 10, 2013). Both specific activities and directed discussions were utilized to create this conflict. Professor Fairbanks described this as seeing "a dissonance" between the student's framework and what actually happened. Responding to a question on the specific things he deliberately did in PHYS 7050 to cause this dissonance, Professor Fairbanks explained,

> They’re doing exercises where they’re having to somehow take a stake, put down their ideas of how the situation’s supposed to work or what the implications are. And then work with that far enough to see if there’s a conflict…if it’s consistent with that and some other idea or observation or what they know happened in a particular circumstance. (Interview, June 12, 2013).

Professor Fairbanks illustrated this in a class discussion about forces acting on a two-block pulley system (Figure 7).

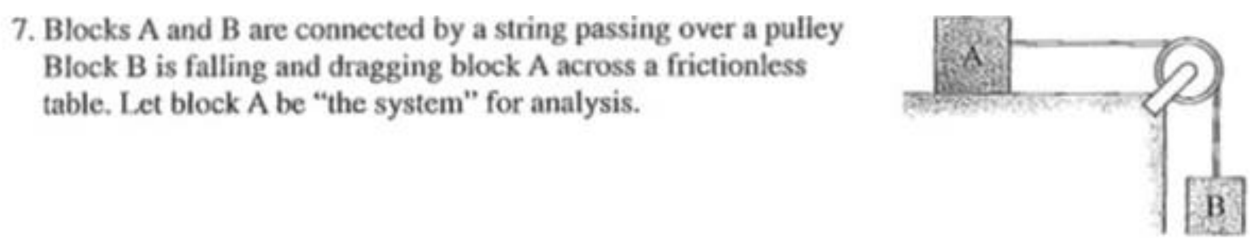

7. Blocks A and B are connected by a string passing over a pulley Block B is falling and dragging block A across a frictionless table. Let block A be “the system” for analysis.

Figure 7. Force Problem Example: Two-block Pulley System. Adapted from “College Physics a Strategic Approach: Student Workbook (Vol. 1),” by R. Knight and J. Andrews, 2007, p. 4-2. Copyright 2007 by Pearson Education, Inc.

After a student drew the FBD on the board and the forces were identified, Professor Fairbanks asked what other issues students might have with this problem. He then brought up that there was no normal force on block B and students might want to add one. Sandra brought up a previous example involving a normal force, which did not relate to this example, indicating a potential confusion about the normal force. Professor Fairbanks addressed this by emphasizing the method of circling the object and identifying all contact forces. This technique confronted the idea that there is always a normal force. Afterwards Sandra expressed a related but non-applicable reason in the current context for the normal force not being present. Professor

Fairbanks recognized this confusion and reemphasized the circling method on the board and re-explained why the normal force was not there.

> [Professor Fairbanks] So they [students] get used to having a normal force everywhere and they want to put it on their free body diagrams and so this identifying with the circle is to help them work through that and say we can't have a normal force if it's not attached, sitting on, or in contact with a solid object.
>
> [Student Sandra] Not perpendicular?
>
> [Professor Fairbanks] It's not touching a solid object. Normal forces are properties of a solid object, because they are solid. (Class 3 Observation, June 10, 2013)

Like the previous category, research-based pedagogy was utilized in the instruction. As students' ideas were expressed, they were matched up with these common conception,s and appropriate strategies were chosen to develop conflict between the students' ideas and the science of the phenomenon. As Professor Fairbanks explained the goal, "being aware of, from the research side of what people have found to be common conceptions that the students have" (Interview, June 5, 2012). This conflict was the catalyst that motivated the students to change their ideas.

Limitations in this category were identifying preconceptions and conflicts with scientific concepts, not developing an underlying framework to explain it, or metacognitive skills for students to self-evaluate their conceptions. Professor Fairbanks pointed this out in describing the lower FCI gains for the PHYS 7050 students in the 2013 course compared to the 2012 course, "They definitely were engaging the misconceptions…and so what it means is, they were understanding their misconceptions but…their conceptual framework didn't quite congeal" (Interview, July 31, 2013).

In reflecting on changes in his perspective on physics teaching and learning, resulting from the first year of collaboration, Professor Fairbanks acknowledged this approach as focusing on data comparison instead of model building. He stated,

> The way we ended up designing the activities…we are trying to get them to compare data when we want them to be comparing the underlying models…. We tend to focus maybe on that data level of things and so that is something that in a way that a lot of our activities are written that should be different. (Interview, July 23, 2012)

4. Students' Learning Approach

How students learn, how they develop their concepts and what is involved in conceptual change were identified by Professor Fairbanks as the key elements of this approach. Describing PER, Professor Fairbanks commented,

> At the core it's understanding. Trying to develop an understanding of how students learn, particularly how they learn physics; those things that are particular to learning and understanding physics. So, how do students learn? What's going on? What are they thinking? What's going on in their head when they're trying to learn physics, and when they're trying to appropriate some new idea, particularly physics? (Interview, June 10, 2013)

The emphasis on the students' learning denoted a student-centered approach in contrast to the teacher-centered approaches of the previous categories. Professor Fairbanks highlighted this idea in describing what a successful discussion in a classroom looked like. He described,

> They're [students] going to understand it better and they're going to get more of the idea if it comes out of them and they come to that conclusion and they see how that works then if they're just told that idea. (Interview, July 10, 2013)

The instruction centered on facilitating the students expressing their ideas. Professor Fairbanks explained, “Make them defend those ideas and think about them and think of whether they’re consistent with other things” (Interview, June 5, 2012). The engagement of the students’ ideas was central in the teaching instruction. Explaining the attitude he wanted to project to the PHYS 7050 students toward students’ ideas, Professor Fairbanks stated,

> The students’ ideas on the topic are really important…the students can’t change their ideas if they don’t know what they are, if they haven’t actually engaged the ideas that they have. You can’t help with that if you don’t know what they are. So, hopefully that comes through and I hope it’s explicit…it certainly is embedded in everything you do. (Interview, June 12, 2013)

Professor Fairbanks affirmed one key component in this instruction was “discussions… that let the students’ ideas come out so they can confront those ideas more and really struggle with them” (Interview, July 31, 2013). Implied in this approach was the need for metacognition within the students. Fairbanks lamented, “The students aren’t very metacognitive. They aren’t thinking about their own learning and their own conceptions” (Interview, June 5, 2012). Though acknowledged for the first time, in this category, the development of metacognition was not something that was explicitly emphasized in the instruction. As shown in Professor Fairbanks’ description of modeling instruction, the students’ thinking about their learning was encouraged, hoped for, even a byproduct of the experience, but not a process that was explicitly taught to the students. He remarked,

> The modeling approach or the sense that what’s being done in this 7050 class is very similar to being, what’s being done, what should be going on in their teaching… then hopefully that models something that changes the way they think about their relationship

> in the class and their role and that's the other thing. By putting them in the studio you're putting them in an environment in which hopefully it's easier for them to transform…hopefully forces them or makes them or gives them an opportunity to think differently about their role. (Interview, June 12, 2013)

Like in the previous category, students' ideas were highly valued by Professor Fairbanks. Now, Professor Fairbanks' understanding of students' ideas was more sophisticated, connecting where students' ideas originate with theoretical ideas from conceptual change. He used this knowledge to focus the instruction. The forming of these connections was shown in Professor Fairbanks' description of changes, occurring in his view of students' teaching and learning after the first year of the collaboration. He cited the influence of his exposure to conceptual change models. He stated, "Getting the perspectives of different conceptual change models…whether students have rationale kind of viewpoint or a bunch of disconnected ideas." (Interview, July 23, 2012). He connected this with his previous ideas on students arriving at their ideas experientially. He continued,

> Still they came to it for some reasons…these are intelligent human beings and so that close connection helps to reinforce and makes it easier to treat the students in a more positive light….It's a humanizing kind of an effect that brings you closer to the learning process and the struggle that they are going through and that is always helpful.
> (Interview, July 23, 2012)

His perspective progressed to focus on the students' ideas - how students were thinking and why they were thinking that way. He explained,

> So that's, I think, another effect in my thinking. It focuses me on thinking about well what are the ideas and why do they have these…more focused down on how the students are thinking about it. (Interview, July 23, 2012)

Students' ideas were recognized by Professor Fairbanks as context-dependent in this category. Describing how students learn physics in his initial interview, Professor Fairbanks discussed the limitation of students' experiential-based ideas. He stated, "How they construct their own experience given certain ideas, which may work in that range of experience. But it may not work outside of it and therefore is not wrong, but it's totally limiting" (Interview, June 5, 2012). Professor Fairbanks emphasized this again in talking through potential students' answers on the FCI near the end of the course. He expressed,

> They can have pretty good ideas and still get some of these wrong because they are connecting it to a certain kind of experience and it doesn't mean that they have a particular misconception or they are thinking in a different way. (Class 12 Observation, July 23, 2013)

Helping students understand the context limitations of their ideas was one of the challenges identified in this category. Professor Fairbanks illustrated this in a class discussion about momentum and students' challenges with it. He said, "So once they [students] get hold of a conservation law, they want it to be a general rule they can use everywhere" (Class 9 Observation, July 11, 2013). Another challenge was identifying embedded ideas within students' experiences, which again was limited to a specific context. Professor Fairbanks illustrated this in a class discussion on the connection between force and motion. He began,

> What is key here and hard to get into, work it into our way of thinking, is that forces causes change - changes in motion. They don't cause motion. And one of the key

misconceptions that is really fundamental and shows up a lot is this idea that motion requires force. (Class 3 Observation, June 18, 2013)

Professor Fairbanks then illustrated why students often develop this idea that "motion requires force" from their personal experiences. He continued,

> Because we live in a high friction world where we don't often think about the friction. If I want this chair to keep going I have to keep pushing…so we end up with the idea that velocity is proportional to force…because we are thinking about our force that we are applying, but not about friction as a force. (Class 3 Observation, June 18, 2013)

While Professor Fairbanks continued to utilize research-based pedagogy in his instruction, now there was a deeper understanding of the theoretical basis of this pedagogy and a greater ability to apply the underlying principles on his own. Professor Fairbanks demonstrated this several times in an introductory lesson on forces, dissecting how students mislabel concepts which led to inconsistent ideas. He explained,

> The acceleration they might just call gravity and the force they might just call gravity, they call everything gravity. So you ask them what is the acceleration and they will say gravity. It doesn't even make any sense. Gravity is a force. (Class 3 Observation, June 18, 2013)

Later in the same class, students responded to Professor Fairbanks' questioning. This demonstrated how not fully understanding the meaning of a term can lead to confusion and inconsistency in the application of these concepts. In a discussion about the normal force, Professor Fairbanks questioned the class,

> [Professor Fairbanks] First off the name, why is it called normal force? Does anybody know?

[Student Loretta] It's normal.

[Professor Fairbanks] That is what the students say normal force, natural force, you know, it's just there. It is always there that why it is the normal force. But normal is the mathematical word for perpendicular

[Student Lynn] Oh! (Class 3 Observation, June 18, 2013)

This category emphasized the understanding of students' ideas. Professor Fairbanks extended beyond just identifying the ideas, by focusing on trying to understand the context which led to the students' ideas. With an emphasis on the context of ideas, connections were formed between the ideas forming rudimentary frameworks. Professor Fairbanks' thoughts on the importance of students' thinking about their ideas showed a basic valuing of metacognition, but not an intentional developing of it.

The major limitation in this category was connecting students' ideas into a consistent conceptual framework. In reflecting on the students' learning, Professor Fairbanks identified that the students had improved in their ability to identify the proper pieces of their ideas, yet he noted, "You haven't really gotten them to have constructed that framework that's going to be robust" (Interview, July 31, 2013). Without a robust framework or coherent picture of how things work, students were left in conflict, which may limit their learning. In debriefing a student-led activity on projectiles, Professor Fairbanks discussed this as a cause of students' frustration. He stated, "Students get frustrated if they… not able to come to and form a coherent picture. Right? For that is what they want to do" (Class 7 Observation, July 2, 2013). He continued to explain that in confronting students' ideas, instructors often confuse the students' ideas and fail to help the students develop a consistent alternative set of ideas. He emphasized, "You messed up their ideas and they haven't been able to construct a coherent picture of how to think about it. Right? And they know they are going to be asked to do that. So that is their conflict" (Class 7 Observation, July 2, 2013).

5. Conceptual Change Approach

In this category, Professor Fairbanks' focus shifted from students' ideas to their framework, which provides the logical basis for their ideas. The ideas expressed here align more closely with traditional conceptual change theory (Posner et al., 1982). The emergent ideas of this category were all characterized by a focus on changing students' framework while encompassing a wide range of ideas. To further delineate these ideas on the basis of sophistication, this category was subdivided into a novice view and an expert view.

Novice view.

The focus of Professor Fairbanks marked a progression from emphasizing individual ideas to connecting these ideas within a framework. Professor Fairbanks illustrated this transition in discussing how the first year of collaboration changed his thinking on his framework by helping students identify their ideas. He replied, "Are they thinking about why they thought that this was going to happen and are they thinking well what is the explanation for why this happened? So you really [are] comparing things on a more underlying model level" (Interview, July 23, 2012). The realization and emphasis on the interconnectedness of students' ideas developed a better framework for understanding. The evolving of this idea in Professor Fairbanks was expressed in his reflection on students' ideas after the second year of the collaboration. He stated,

> Instead of idea by idea of getting them to recognize something broader about how they're thinking about trying that. I don't know how you do that exactly, but maybe we need to recognize more than these conflicts of individual ideas…do I do enough to try to help

> them recognize how their ideas connect to each other and therefore develop a better framework (Interview, July 31, 2013).

On the novice side of this category, the understanding of how to change students' frameworks was still a collection of abstract ideas that were not fully integrated. These elements were evident as Professor Fairbanks discussed his understanding of teaching for conceptual change near the beginning of the second year of the collaboration. He explained the goal by stating, "We're trying to help them on a path where they can change the framework that they have by which they're understanding" (Interview, June 12. 2013). However, when he tried to explain how to do that, his ideas while pertinent were not integrated into a method for achieving a changed framework. He continued,

> How do we do that? So there's the theoretical background and having a picture of okay, how does this all work? How do people change their conceptual framework?...So, [the science education professor] was doing some of that and a lot of what overlapped between the things he would talk about and the things we'd be doing as we worked on the specifics was the general ideas of how you get students to see a dissonance between their framework and what actually happens or different pieces of their framework not making sense together, and then forcing them to engage those things so that then they have to find some way to resolve that conflict. (Interview, June 12. 2013)

A clear distinction was made between the theoretical background the science education professor taught and the practical work the physics professor was leading. In Professor Fairbanks' articulation of the process, general connections were acknowledged, but a general, more abstract language was used showing a limited integration of the theoretical with the practical work. The novice lacks an integrated view of his or her framework. Professor Fairbanks illustrated this in the students' [novice] approach to activities while doing practical classwork where the larger framework is not considered. He reflected,

> They [students] weren't able to do things where they had that larger framework in their minds while they were doing something on the more practical…when you're teaching, it's always on a practical level….So you would have liked to have more opportunities for them to reflect on, in the context of a particular activity the connection between what you're doing in the immediate activity and how and why it fits into the bigger framework. (Interview, July 31, 2013)

Metacognition was recognized as a vital step in developing a better framework by Professor Fairbanks. His reflection on his own teaching, following the first year of the collaboration, illustrated this as he defined what metacognition looked like in his teaching. He reflected,

> Teaching to future teachers or present teachers is different because there is much more metacognitive, you are thinking about why you are teaching, you are thinking about your teaching and as you are talking about these things, why you do what you do. (Interview, July 23, 2012)

In the novice view, the need to develop metacognition in students was clear, but the means to do so was still in the formation stage. Professor Fairbanks showed this need in a classroom discussion on Hooke's law. In the discussion, he was leading students through a Hooke's Law lab procedure. The PHYS 7050 students had just completed the lab and were preparing to lead in the studio classroom. Discussing the focus for the students' learning through the procedure, he stated,

> You want them not just to do it, but then to think about it. Once they have this nice procedure and it's a perfect procedure they can get bad data and then just go on merrily along and they actually got to be reflecting on it. Is this working? Are we actually getting accurate information? (Class 8 Observation, July 9, 2013)

The goal of having the students think about what they were learning was clear. However, Professor Fairbanks did not elaborate on how to do that. Again in the novice view, the essential characteristics were recognized by Professor Fairbanks, but the means to achieve them were not articulated. The integration of these into a coherent framework was lacking.

Expert view.

Abstract ideas contrasted with an expert-integrated view within the framework was thought of in more concrete ways. The physics professor explained the difference between novice and expert views of a framework in the context of applying mathematical theory to graphs, teaching a class to physics majors instead of introductory physics students. He elaborated, "You're using these mathematical tools which if they really have a deep understanding of…more expert then in some sense, it's not as abstract" (Interview, July 31, 2013). He further illustrated with a specific example of applying calculus to graphs. To an expert this was a concrete idea and not the abstract notion it was to a novice. He explained,

> If you're integrating to do the area under a curve or taking a derivative to get a slope and you have a real fundamental understanding of physically, What does this equation represent? Why am I doing this operation, what does it represent? Then you're thinking of it in a much more concrete way. Whereas if the students don't have that understanding, then it's very abstract to them because they're following a procedure and they're saying, okay we take the equation, we do this, and then you do this, and they

> don't really understand why they're doing those procedures and so to them it's a procedure…it's an abstract dot. (Interview, July 31, 2013)

This same novice-to-expert pattern of moving from abstract to concrete was seen in the physics professor's conceptions of teaching for conceptual change. At the beginning of the second year, reflecting on teaching for conceptual change independently, the physics professor demonstrated a more abstract novice view of teaching conceptual change ideas. He elaborated,

> I think the lack of a little more coherent presentation of the conceptual change ideas is lacking a little bit. I mean I'm trying to do a little bit better but I can't make up for that really. I can't successfully take that role totally. (Interview, July 10, 2013)

This opinion contrasted with a second excerpt where Professor Fairbanks reflected on what developed during that second year as his method for teaching for conceptual change. The ideas were much more concrete and developed. Professor Fairbanks explained,

> It went from content and analyzing the content to the close look of, in this particular circumstance, what are we trying to accomplish? So, they were learning about teaching conceptual change in the context of this worksheet - motion diagrams. Doing that and then the bigger picture came in later. (Interview, July 31, 2013)

Professor Fairbanks explained how this approach for teaching conceptual change integrated with his conceptions of teaching physics. It illustrated how he was integrating the conceptual change framework into his practice. He continued, "But instead of getting that framework first, which actually is the rule of thumb in physics teaching is, you go from the concrete to the abstract not the other way around. So, I guess we followed that in general" (Interview, July 31, 2013).

This process of going from the concrete to the theoretical in teaching conceptual change was illustrated in a class discussion on motion diagrams. The context was Professor Fairbanks' leading a discussion following the PHYS 7050 students' first teaching experience in the studio class. Professor Fairbanks began,

> [Professor Fairbanks] So what makes this an active learning environment?
>
> [Student Loretta] Immediately applying the concept to mention that there is a clear understanding as far as of being able to transfer... to a connection, an application in real life. Black and white on paper.
>
> [Professor Fairbanks] So they are being active because they are actually doing the worksheet and having to write something down. How else are they being active? (Class 2 Observation, June 13, 2013)

In his summary of the students' answers, Professor Fairbanks provided specific examples of the concept of being active from activities just observed in the concrete experience of the students' teaching in the studio class. The students further expanded, offering more specific examples. Amy continued,

> [Student Amy] I thought one thing that Bettie said that was really good. They were working through the problems, but if they are working through them totally incorrectly, the instructors and TAs are still standing over them….They get to work together, but there is still supervision of them working together. Like a study group with a tutor watching over them.
>
> [Professor Fairbanks] You touched on what I was trying to get to is that they are active because they are actually having to talk about, not just do the worksheet. It's not just all in their head as well. They are having to talk; they are asking questions. There is an interaction both with each other and with the instructor on a small scale. (Class 2 Observation, June 13, 2013)

In this discussion, Professor Fairbanks used the concrete activity and experience of teaching motion diagrams as a vehicle to discuss the theoretical idea of an active learning environment.

In the expert view, a shift occurred from connecting ideas into a framework to changing or expanding the framework. Professor Fairbanks illustrated this in discussing students' understanding of forces and the process necessary for students to understand. He explained,

> You expect that they are identifying the forces and giving directions and stuff, that is the first step. Kind of putting together and adding and connecting with acceleration and all that, that's more complicated, it's a bigger thing and their framework has to expand in order to cover all that. (Class 4 Observation, June 20, 2013)

The aim in the instruction is a "better framework", as shown in another excerpt from a later class's instruction on forces where Professor Fairbanks stated, "Because we know things with different mass do fall differently and we are actually trying to get to point where we can have a better framework for why that happens" (Class 7 Observation, July, 2, 2013).

A more sophisticated understanding of a framework allowed it to be integrated into the instruction. The conceptual change framework was utilized by Professor Fairbanks to evaluate his pedagogy. The following excerpt on how the first year of the collaboration influenced his teaching in the following year demonstrated this. Professor Fairbanks reflected,

> Having a more solid kind of theoretical framework for conceptual change…so in choosing particular assignments…I think I look at it with a little different view and probably make somewhat different choices…from a framework to help me gauge what I think is going to be most successful of bringing about the conceptual change I'm looking for. (Interview, June 12, 2013)

Additionally, there was a concrete aspect of adapting the framework to the distinct personal teaching style of the physics professor.

> I know that the framework they're getting for conceptual change is coming from our discussions of these particular activities. So I know that I want to in class talk about, Okay. Well, you know, what should be going on here? What do you think is going on? What are the students thinking when they do this? Why are they asked to do this? And kind of getting to those issues from that activity. So then I look at the activity a little bit differently because it's going to be the vehicle that we're going to use to get into that discussion....Not just an activity where it's practice for them. But something we're also going to use to try to ferret out the overall strategies. (Interview, July 10, 2013)

Professor Fairbanks utilized this strategy in leading a class discussion on an energy simulation the PHYS 7050 students led in the studio class. Focusing the discussion on the predictions asked for in the lab, he then led the students in expounding the strategy for the predictions and how that tied in with the framework of teaching for conceptual change. He began,

> [Professor Fairbanks] So what did you all learn about using simulations?
>
> [Student Sandra] We really enjoy it. The kids…they did get a lot out of it….That's because you really prompted them to not just play with it. Right? They would hypothesize before they would adjust it so they weren't playing around randomly…
>
> [Student Amy] One of the things that we did in our group was they made their prediction. Then once they had made their predictions I just asked them like what do these predictions that you just made line up with stuff that you stated on the first page…
>
> [Professor Fairbanks] You want their real predictions to come out. Right and their real thought process....Whatever you do you got to get them to the point where they are

> engaged in thinking about what that concept is and how does it apply to that situation. (Class 12 Observation, July, 23, 2013)

The emphasis was placed on the students' engagement in thinking about the concept and its specific application. This process required a developed metacognition in the students. In the expert view, the importance and utilization of metacognition was further enhanced. Professor Fairbanks, at the end of the course, while conceding that the students had limited opportunities for this metacognition, outlined specific activities to enhance it. He stated, "More opportunities for them [students] to reflect on in the context of a particular activity the connection between, what you're doing in the immediate activity and how and why it fits into the bigger framework" (Interview, July 31, 2013).

The instruction in the expert view focused on helping students "on a path where they can change the framework that they have by which they're understanding", mentioned Fairbanks. (Interview, June 12, 2013). An emphasis was on the students' developing the tools to evaluate their own learning. Fairbanks explained,

> Hopefully, we've given them the tools that they can help to identify when they're understanding or not understanding and be able to, on their own, learn things and change their understanding. And if they're to teach something so that they've got a framework so that they can actually go and feel like they can prepare themselves to be able to teach. (Interview, June 12, 2013)

To accomplish this, there was a concerted effort to make explicit tacit understanding, especially in the underlying structure of activities. Fairbanks elaborated,

> Well, the way most of the activities are structured you see that part of it is…you've asked them to do this. Well, why have you asked them to do this?...So how constructing

> assignments, some of it is to force the students' ideas on the topic to emerge for them to see and for the instructors to see. (Interview, June 12, 2013).

The physics professor emphasized the importance of both metacognition and making tacit understanding explicit in the following discussion with the PHYS 7050 students. It concerned the design of a force lab they performed and were about to lead with introductory physics students. He expressed, "They [students] don't want to think about why they are being asked to do things. They don't want to be metacognitive. Most of us don't. And so…they have to be prompted to be thinking about these things" (Class 6 Observation, June 27, 2013).

He specifically demonstrated the need for prompting by pointing out a section in the lab the students had all just completed, requiring them to compare different results. He continued,

> And you all came to the same mode in a sense that you got into the point of putting these two things in boxes. You weren't explicitly asked. That was the point was to compare. You didn't have to do that to answer the problem, because you just went by happily along and you had no thought as to why you were asked to put those things in those two boxes, right? (Class 6 Observation, June 27, 2013)

Having identified how easy it was for the PHYS 7050 students to not be metacognitive, he then challenged them to apply this to their students and provided specific advice on how to help the students be more metacognitive. He concluded,

> And if you are not thinking about why you are being asked to do it. You know that the students are not thinking about why they are being asked to do what they are doing. And so that is part, which is why you are there as an instructor is to slow them down at times or to prompt them. (Class 6 Observation, June 27, 2013)

Finally, in the expert view there was the ability to apply a framework to other contexts. Professor Fairbanks illustrated this in a limited scope when discussing what he learned about teaching for conceptual change in the context of teaching future teachers in his introductory physics classes. He shared,

> More thinking about activities in a class or what I ask some of the students to do and not thinking so much as idea to idea, a laundry list, but trying to think more about connections between things. That's the main way I think it would impact my intro teaching. (Interview, July 31, 2013)

Structural Relationships between Categories

These categories represent qualitatively different approaches to teaching for conceptual change. There was a hierarchical, inclusive relationship between them. As Table 3 indicated, the categories were arranged in a progression toward more sophisticated ideas of teaching for conceptual change. Higher categories include an awareness of the aspects of the lower categories, representing further growth and development of the ideas. Lower categories do not share the same awareness of the aspects of the higher categories. An important acknowledgement was that the experience of teaching for conceptual change was more holistic and contained aspects of all the different categories simultaneously. The distinctions drawn in the categories were for descriptive and analytical purposes. These hierarchical categories allowed the growth and development of conceptions and practices of teaching for conceptual change to be analyzed. Therefore, the growth and development process of these within the physics professor, along with the major influences, are examined next.

Change in Conceptions and Practices of Teaching for Conceptual Change

This section examined the research study's related questions (1) What is the evidence of change in a physics professor's conceptions of teaching for conceptual change? (2) What is the evidence of change in a physics professor's practices of teaching for conceptual change? These questions were considered through six different periods of the study: preliminary, initial collaboration, planning, independent practice, resumed collaboration, and extended practice (Appendix K). The preliminary period focused on evidence of the physics professor's conceptions and practice prior to the beginning of the collaboration. The initial collaboration period focused on the physics professor's conceptions and practices during and after the first summer of collaboration. The planning period examined the physics professor's conceptions and practice prior to beginning the second year and through the first two classes of PHYS 7050 during the 2013 summer semester. The independent practice period covered the time when the physics professor was teaching PHYS 7050 by himself (Classes 3-8) during the 2013 summer semester. The resumed collaboration period examined the second year of collaboration beginning with Class 9 through the end of the 2013 summer semester. The extended practice looked at the physics professor's conceptions and practices as exhibited in teaching a different class following the collaboration. This occurred in two sessions of the upper-level lab course PHYS 3000 in October 2013.

The physics professor's conceptions of teaching for conceptual change were considered first through the identified periods of the study. The evidence presented included the physics professor's expressed words and acts concerning these. This evidence was then used to position the physics professor's conceptions within the emergent categories discussed above for each period allowing any progression or change through the course of the study to be indicated. A related analysis of the changes in Professor Fairbanks' language usage was included to document the changes in the specific language he used to describe his conceptions of teaching conceptual change. This was followed by repeating the process with his practices of teaching for conceptual change.

Conceptions of Teaching for Conceptual Change

Preliminary period.

Prior to the collaboration with the science education professor, the physics professor showed a general familiarity with teaching conceptual change from the context of the physics classroom. In the initial interview, the physics professor expounded on his views of students' ideas and their role in teaching. He stated,

> You're not just introducing a new idea. You're actually trying to get them to re-interpret their twenty-some-odd years of experience and see it and construct it in a new way. So it's vitally important with the ideas that they come in with and how they've put together their experiences into the ideas that they have…which may work in that range of experience. But it may not work outside of it and therefore it is not wrong, but it's totally limiting. (Interview, June 5, 2012)

His belief that students enter a physics class with prior conceptions about physics principles based on their personal experiences was expressed. Due to their experiential basis, these students' conceptions have value and were not to be discarded and replaced, but understood and built upon to become more predictive for situations outside their experiences. His approach for achieving this was summarized as:

> The teaching, I think, needs to be directly responsive to where the students are….

> If they have a misconception, they're going to change most effectively if they're actually able to recognize the difference between what their idea of how things work and actually seeing it work differently….You're not going to change their idea if they have to be left in a way where they're just rejecting one idea and they don't have an adequate alternative whatever--theory or whatever you want to say. A model of what's going on. (Interview, June 5, 2012)

His approach was learning-oriented, focusing on students' conceptions and revealing their differences with scientific ideas and providing alternative explanations. While the teaching was focused on the students, a strong emphasis was placed on the teacher's facilitating students to change their ideas. Within the emergent categories, the ideas fall between the Students' Ideas and Students' Learning categories. The focus on revealing differences between students' ideas on how things work and the observation of how it works pointed to the creating conflict emphasis within the Students' Ideas category. Yet, his recognition of the requirement for an alternative theory, developing a limited framework of consistent ideas, is a characteristic of the higher category of Students' Learning.

On Professor Fairbanks' framework of conceptual change, his earlier expressed approach loosely aligned with the conceptual change theory of Posner et al. (1982). This theory initially creates a dissatisfaction with the initial idea and then presents alternative ideas that must be seen as intelligible, plausible, and fruitful before they are adopted and conceptual change can take place. However, his general language and limited development of these ideas suggested that his framework was based more on his practical experience of teaching and exposure to PER literature than on the theoretical ideas of conceptual change theory.

Underscoring his limited familiarity and confidence in his theoretical knowledge of conceptual change at this time, Professor Fairbanks' was somewhat uncertain in describing the theory and in self -identifying this as the change he desired from this collaboration. Professor Fairbanks' statement about "alternative whatever theory or whatever you want to call it" (Interview, June 5, 2012) was a clear hesitation seen in what to call this framework that replaces students' ideas. Later in the same interview, Professor Fairbanks, in describing what impact he hoped the collaboration would have on his teaching, highlighted learning more about conceptual change theory and how to apply it. He explained,

> I'm going to be learning more of the theory side of things. Just being exposed to more of the conceptual change, and so it will give me more tools also to help understand how to bring about conceptual change in my students at all levels of the class. (Interview, June 5, 2012)

Initial collaboration period.

After the first year of collaboration with the science education professor, several changes were observed within the physics professor's conceptions of teaching for conceptual change as expressed in his post interview. One of the most important aspects he identified was an understanding of the need for an overall framework for teaching for conceptual change. He mentioned,

> The underlying framework was important, because it [my perspective] was probably more in teaching an intro level class. It was more an understanding of what the literature said works and doesn't work from the physics education perspective…even when it [PER] is digging down to how students are thinking and how students learn; it's usually not putting any overall framework onto that….So I think, it gives a framework which

> have another way to evaluate…whether something is likely to be effective or not or how I should go about or shouldn't go about to think about the student's experience which I think is more powerful than just the physics education research background by itself. (Interview, July 23, 2012)

Professor Fairbanks expressed a change in his thinking from high level ideas common in PER, targeting general misconceptions, to focusing on a more underlying framework of why students think the way they do. Professor Fairbanks discussed a changing perspective on the nature of students' ideas and this influencing the way he connects with students, "a humanizing effect". He elaborated,

> I tended to think of…misconceptions being a pretty firm thing and then having a pretty structured framework. So it's made me have to rethink a little bit, how should I think about and not to try and put them all in the same box as well….The way these ideas develop and so the more of that you get or the understanding of how they might get to those ideas and…whether the whole thing is rationally constructed or whether it is a bunch of ideas, still they came to it for some reasons that are, you know - these are intelligent human beings and so that close connection I think helps to reinforce and maybe it is easier to treat the students in a more positive light. (Interview, July 23, 2012)

The influence of Professor Crefeld's teaching of different conceptual change models, especially the comparing and contrasting of Vosniadou (1994) and diSessa (1993), was evident. Professor Fairbanks' shifting perspective to a stronger valuing and emphasis on how students' ideas form suggested an obvious movement toward the Students' Learning category.

Within his teaching, Professor Fairbanks identified the importance of metacognition for the students, drawn from Professor Crefeld's emphasis on students' explaining their predictions in lab activities. Professor Fairbanks stated,

> Are they thinking about why they thought that this was going to happen and are they thinking well what is the explanation for why this happened? So you really are comparing things on a more underlying model level….You get them to talk more about not just what their ideas are but why. So that they are aware of their thinking in their model….We get to the metacognition idea and it kind of pulls together. (Interview, July 23, 2012)

After the first summer of collaboration, Professor Fairbanks expressed changes in his conceptions of teaching for conceptual change, stressing the underlying framework of students' ideas and the importance of developing metacognition, both heavily influenced by Professor Crefeld's instruction. On the identified continuum of teaching for conceptual change categories, he was solidly in the Students' Learning category.

Planning period.

At the start of the second summer semester, Professor Fairbanks was asked what strategies he had identified in Professor Crefeld's instruction from the previous summer that he planned to implement in his own teaching. He voiced a stronger emphasis on engaging in open discussions where students struggle with their ideas. "Seeing the value in them engaging in the struggle. Not necessarily needing it to come to a sharp point at the end" (Interview, June 12, 2013). Professor Fairbanks acknowledged, "I've gotten more comfortable and there are some instances in which we have some open-ended discussions or I leave things hanging a bit more" (Interview, June 12, 2013).

In Class 2, Professor Fairbanks led the following discussion, demonstrating his increased confidence with leading open-ended discussions. As class began, he asked students to share their observations and impressions from their first interaction in the undergraduate Studio physics class. Bettie, the first student to share, contrasted the Studio classroom with her undergrad experience. She said, “It was very interesting. I wished I would have had that in undergrad. I would have learned a lot more because in my class I just sat there and didn't learn and didn't ask questions.” Professor Fairbanks followed by facilitating more input, “Ok, does anyone want to respond to that?” After several students shared their thoughts, Professor Fairbanks affirmed the sharing and redirected the discussion back to Bettie’s initial statement to further focus the discussion on the type of environment. He summarized,

> “So the comments were really good and a lot of good things were mentioned along there. I think it was Bettie who said she liked it because her class was very passive and passive isn't supposed to be in the syllabus. We are talking about active learning. So what makes this an active learning environment?” (Class 2 Observation, June 13, 2013)

After two students’ input, Professor Fairbanks closed the discussion making this point,

> You touched on what I was trying to get to is that they [students] are active because they are actually having to talk about, not just do the worksheet. It's not just all in their head as well. They are having to talk; they are asking questions. There is an interaction both with each other and with the instructor on a small scale basis. (Class 2 Observation, June 13, 2013)

Professor Fairbanks not only highlighted the importance of students voicing questions and interactions, but he demonstrated it by modeling it through this discussion. This was a common technique used last year by Professor Crefeld, but rarely by Professor Fairbanks.

Professor Fairbanks exhibited limited confidence on leading discussions specifically on the conceptual change framework. In responding to an interview question on what things he observed in Professor Crefeld's instruction that were uncomfortable for him, he stated, "Engaging in some of the discussions about that theoretical framework for conceptual change. Although I've learned a lot, I don't feel comfortable enough to be able to actually lead those kinds of discussions" (Interview, June 12, 2013

Entering the second year, one significant change was Professor Fairbanks' greater understanding of a theoretical framework for conceptual change and how this enabled him to evaluate potential pedagogical resources based on this conceptual change framework. Answering what was a direct influence of the previous year's collaboration on his teaching in other classes, Professor Fairbanks identified,

> Having a more solid kind of theoretical framework for conceptual change and how that, so in choosing particular assignments…I look at it with a little different view…from a framework of to help me gauge what I think is going to be most successful of bringing about the conceptual change I'm looking for. (Interview, June 12, 2013)

Professor Fairbanks demonstrated a limited integration of theoretical framework into his pedagogy evaluation. While still rooted in the Students' Learning category, Professor Fairbanks developing theoretical framework and limited ability to integrate it with his practice included a few aspects of the Conceptual Change – Novice View category.

Independent practice period.

During the second summer semester, Professor Fairbanks taught the first eight classes by himself as Professor Crefeld's schedule only allowed him to teach at the end of the semester. Teaching the class alone necessitated several changes in Professor Fairbanks' approach as he described in the instructional interview. He said, “Last year I could concentrate maybe on the concept—the students’ conceptions and just kind of instruments we use and the framework was being supplied by Professor Crefeld….I could kind of respond and compliment rather than handle it alone” (Interview, July 10, 2013). Later in the same interview, he detailed the changes teaching alone had on his focus. He explained,

> [This year] the focus is much more on everything through that prism of a particular physics activities and teaching a physics class…trying to teach for conceptual change, starting from this concrete example rather than from theoretical side and kind of going toward the practical example. We go the other way, because that’s more comfortable to me. (Interview, July 10, 2013)

With Professor Fairbanks’ approach of teaching from the concrete to the theoretical, he focused more on evaluating the classroom activities from a conceptual change framework. He elaborated,

> Seeing that in whatever activities it is, that you’re trying to get the students’ ideas out there in some way that’s visible to them and to the instructors….The most important thing there is that their ideas have to come out. They have to work with them and they have to be set up in a situation where they can recognize some kind of a conflict. (Interview, July 10, 2013)

Professor Fairbanks identified the key aspects for conceptual change by having the students express and evaluate their ideas. A clearer articulation of these ideas was now given than before. In addition, Professor Fairbanks continued by providing specific strategies to achieve this type of environment where students were sharing and evaluating their ideas and building a framework.

He identified a central strategy in his instruction to do this with open discussions around the activities like those led by Professor Crefeld last year. He explained,

> I know that the framework they're getting for conceptual change is coming from our discussions of these particular activities. So I know that I want to in class talk about… What should be going on here? What do you think is going on? What are the students thinking when they do this? Why are they asked to do this? And getting to those issues from that activity. So then I look at the activity a little bit differently because it's going to be the vehicle that we're going to use to get into that discussion. (Interview, July 10, 2013)

Professor Fairbanks' limited confidence in his expertise on the theoretical framework of conceptual change and tendency to revert to more direct instruction presented challenges to his leading class discussions. Professor Fairbanks displayed an awareness of both of these challenges and sought to overcome them by asserting a greater focus on cultivating class discussions. He remarked, "I'm trying to hold off more on getting in a mode where I'm passing on my great wisdom to students. So keeping those discussions going, and really exploring the ideas, and letting them think through themselves" (Interview, July 10, 2013). In focusing on asking students questions and planning for discussions, he found some success but discovered that by redirecting questions to the students his lack of expertise limited his ability to fall back into more direct instruction on conceptual change. He explained,

> I've sometimes done an okay job where we have a discussion. And we kind of say, "Well, why do you think this is?" So we say, "What are we trying to accomplish by this?" So we're pushing it to them…and they can for themselves, be able to pull that out …once they get the basic idea. So that area it's probably easier for me to not be the

> expert. Sometimes I have trouble in the other thing where I want to…get into a laundry list of things that the students may do or on the material itself, get into more expert mode. But probably the conceptual change is easier to not get into that mode because I don't feel like an expert. (Interview, July 10, 2013)

During this independent practice, a greater integration of Professor Fairbanks' theoretical framework for conceptual change with his instruction was expressed. Specific examples of how he was teaching for conceptual change and helping students develop frameworks were provided. While students' ideas were still the primary focus of his instruction, the idea of developing students' frameworks was more prevalent. Metacognition was not specifically named, but the significance expressed of students' thinking through their ideas suggested an awareness of its importance. While a lack of confidence in his expertise in teaching conceptual change was voiced, he expressed ways that he overcame this by focusing more on the students expressing and processing ideas than his sharing of information. All of these aspects expressed by Professor Fairbanks, moved his conceptions of teaching for conceptual change towards the Conceptual Change – Novice View category.

Resumed collaboration period.

Additional changes were reflected in Professor Fairbanks' conceptions on teaching for conceptual change following the resuming of his collaboration with Professor Crefeld. Prior to Professor Crefeld's teaching, Professor Fairbanks was trying to model much of what Professor Crefeld did the year before. He stated,

> So I had to reflect a lot more how do you—what am I doing when I lead those kinds of discussions, how am I reacting to students' ideas?...Realizing when I was kicking into

> other kinds of modes. So trying to model the right kind of approach…some of the things that [Professor Crefeld] modeled for me last summer. (Interview, July 31, 2013)

The expressed introspection of Professor Fairbanks suggested a deeper metacognition process in his thinking about his teaching. The challenges faced by Professor Fairbanks in his independent practice made him more focused and receptive when Professor Crefeld began instructing and modeling teaching for conceptual change this second year. Fairbanks elaborated,

> He [Professor Crefeld] talked a little bit more explicitly actually this time about what he's trying to and how it works when he was trying to lead those kinds of discussions….I felt like I needed that lesson earlier… I was struggling with being able to lead those kinds of discussions. (Interview, July 31, 2013)

Another change in Professor Fairbanks' reaction to Professor Crefeld's instruction centered around a Ted Talk (Gopnick, 2011) on children making hypotheses. Professor Fairbanks explained, "I think last year … I don't think I had a real clear idea of how it fit in as much" (Interview, July 31, 2013). This year he connected how easily the children made hypotheses with their lack of a framework. He stated, "Why they're so flexible is there's no framework that constrains them from having particular ideas" (Interview, July 31, 2013). As he contrasted the children's approach with that of an expert, he remarked,

> It isn't that they [an expert] go back to being childlike, and in fact they're approaching it in a very different way, but it isn't that they have no framework. It's that they understand the framework so well that they can make changes or they can understand the implications of changing one idea that's connected to a lot of other ideas. (Interview, July 31, 2013)

Recognizing these characteristics of an expert, he then applied it to developing students into experts. He identified that metacognition was a key element which separated experts from novices. He stated,

> How do you get students who've got—who built up all this framework, some of it good, some of it not so good… what we would call the novice….How do you get them to do a more expert-like approach….They have an idea of how things work, but they haven't really thought about that at all. So they're not metacognitive at all about their ideas and so, they don't really have an interest in challenging those ideas. (Interview, July 31, 2013)

Professor Fairbanks' focus centered on students' frameworks, recognizing that they contained both good and not so good ideas, and how to change these frameworks. Professor Fairbanks also acknowledged a change in how he started viewing the FCI distractors, resulting from a connection of ideas, not just one misconception and the implication this had on his approach. He explained,

> Going through the FCI and the distracters, it occurred to me, which I hadn't really thought about it until we did it. There were quite a lot of distracters that were not just one idea, misconception but several misconceptions. I hadn't really realized that to the same degree and that's certainly one reason it makes some of those ideas so stubborn, so difficult to change, but it's that you have to go about it a different way….In the end, all these ideas connect to other ideas and so backing up a little broader picture. And I hadn't really thought that way before this summer. (Interview, July 31, 2013)

Recognizing that often the students' ideas were not isolated but connected and contextual, Professor Fairbanks began to show a shift in his thinking to focusing more on changing students' framework than their individual ideas. He elaborated,

> Instead of idea by idea, of getting them to recognize something broader about how they're thinking about trying that. I don't know how you do that exactly, but maybe we need to recognize more than these conflicts of individual ideas and do we do enough, do I do enough to try to help them recognize how their ideas connect to each other and therefore develop a better framework. (Interview, July 31, 2013)

While a change in his thinking about focusing more on developing students' framework was clear, he was still searching for the specific methods to do so. Applying his description of an expert you can see how Professor Fairbanks' understanding of a conceptual change framework was now allowing him to try new ideas and methods. He understood his framework as shown in his reflection on the central focus of teaching for conceptual change as he stated,

> You have to get their ideas out there for them to recognize as well as—and in fact sometimes it's easy to fall back on trying to understand their ideas just so we know where they're going wrong, as opposed to getting the ideas out there in a way that they can recognize what their ideas are. (Interview, July 31, 2013)

His focus was clearly student-centered with a distinction made from making students' ideas visible for the teacher to identify issues, as he had expressed in the past, to making students' ideas visible so students recognized what their own ideas were. He continued,

> And so it's got me thinking…we aren't good enough or clear enough in what we do sometimes as to make sure that you're getting them to focus on their ideas. And in a way that, then, they can see some separation between their ideas and how something works or

> how they think something works and they can make those comparisons, get some dissatisfaction going there and actually start to think about the consequences of their ideas. So I think that they can't change the framework if they don't even recognize it's there or that their opinion is just kind of a reaction to everything rather than being something that they reason from. (Interview, July 31, 2013)

Within this explanation, Professor Fairbanks articulated elements of conceptual change and specifically named them, such as dissatisfaction being produced from students identifying "separation between their ideas and how something works". Another important distinction was the students' framework identified as "something that they reason from". He articulated further what this ideally looked like in the class,

> They got the lesson in front of them and they got the thing that they're working on ideas of the particular misconceptions and why we're doing it and they're seeing how that works with an understanding of a bigger framework. (Interview, July 31, 2013)

Still, Professor Fairbanks recognized his limitations in achieving this in the class. He reflected,

> You would have liked to have more opportunities for them to reflect on, in the context of a particular activity the connection between, what you're doing in the immediate activity and the how and why it fits into the bigger framework. (Interview, July 31, 2013)

During this period a stronger emphasis on students' frameworks was expressed, including a more detailed description of a framework being made up of interconnected ideas and used as a foundation from which to reason. Professor Fairbanks' instructional focus was identified by getting students to express their ideas and 'think about the consequences of their ideas'. Metacognition was identified as a key to changing students' frameworks. Professor Fairbanks articulated what conceptual change looked like in the classroom, but was still developing the specific methods to achieve this. Professor Fairbanks expressed conceptions of teaching conceptual change were now in the Conceptual Change category, developing more toward an Expert View, but with some aspects of the Novice View still apparent.

Extended practice period.

Following the completion of the second summer semester of PHYS 7050, a set of follow-up observations were conducted with Professor Fairbanks in the fall semester. These occurred in PHYS 3000, an upper-level lab course for physics majors. Two PHYS 3000 classes were observed in the middle of the course with a follow-up interview conducted afterwards. The context of this extended study was to ascertain to what extent Professor Fairbanks' conceptions and practices for teaching for conceptual change translated to a different environment. Because the upper-level lab course was the only course taught by Professor Fairbanks during the fall semester, the choice was limited. Professor Fairbanks expressed his goal for the class was to change the students' approach toward labs. He stated,

> I'm trying to change their [students'] approach to a little bit more sophisticated, a little more research-oriented kind of approach….That they start thinking about things, the physics of it, as they're doing it… They're figuring out the physics so that they can ask the right questions and say, Is this behaving the way we think? How are we going to analyze this thing? (Interview, October 9, 2013)

His emphasis was changing students' framework for approaching labs. Changing from a framework of following "cookbook stuff" where everything was laid out to a physics framework used to evaluate and lead their investigations, Professor Fairbanks' goal was a specific type of conceptual change, though not expressed in those words. His emphasis on the students' thinking and reflection during the lab was applied metacognition.

Professor Fairbanks detailed his idea of the students' framework in terms of understanding models. He explained,

> What I want them [students] to understand to connect up to as the role of experiment as to testing a model and evaluating whether it's working or not and deciding on whether the experiment needs to change or whether the model isn't actually what it says (Interview, October 9, 2013).

The focus was, "How well is our model working?" He illustrated this with a spring experiment recently conducted where students attempted to fit a straight line to data to find the y-intercept (B). He elaborated,

> If it [results] doesn't fit the model, why would we fit a straight line to it to extract B. If drag force is not proportional to velocity, B doesn't have any meaning. Because the model's not working. So that data doesn't help us get a better value of B. So, you also find out the limits of where the model worked…so that's the context that I tried to create. (Interview, October 9, 2013)

In the observed class, Professor Fairbanks described his previewing the experiments by discussing the historical context illustrating the scientists' model surrounding the experiment, and how the experiment affected their model. He elaborated, "The most important part is what was their model? Not as much interest in how they got to that model, but what was their model going into this and why was this then an important experiment?" (Interview, October 9, 2013).

When asked what influence the collaboration over the past two summers played in his planning and teaching of PHYS 3000, Professor Fairbanks responded,

> Being willing to try to move to something that was a little bit more open-ended for them than what I had done, say, three years ago in which it was much more of a manual….

> Also, thinking about more of what the students understood coming into it and where they were. (Interview, October 9, 2013)

No clear link to conceptual change was articulated. Ideas, such as open-endedness and thinking about students' understanding, connected with practices associated with conceptual change, needed more explanation. Professor Fairbanks contextualized the open-ended idea in his description of the course. He stated,

> The upper-level lab is about the role of experiments and the scientific approach and critical thinking and scientific writing. But then there's also a chance for them [students] to engage interesting ideas to see how experiments connect with that…getting enthused by the ideas. (Interview, October 9, 2013)

Professor Fairbanks mentioned students engaging ideas and connecting them with the experiments, but does not clearly articulate whether these were their own ideas or scientific ideas. His connection to getting 'enthused by the ideas' linked it more toward novel scientific ideas. He continued,

> It's also an opportunity – it turns out to fix some holes or deepen their understanding of certain topics, so the content is not really the main goal of the class.…Any content they're engaged in they are getting some kind of knowledge, but there's no particular thing that everybody has to [learn]. We want to make sure everybody learns in that class. (Interview, October 9, 2013).

Professor Fairbanks language describing the learning showed it was individualistic. He appeared more focused on the idea of students having a deficit of knowledge, needing to be filled, as opposed to a framework of ideas, needing to be expanded or modified.

Throughout his description of the class, Professor Fairbanks' conceptions of teaching conceptual change were vague. While not specifically couched in the language of conceptual change, some conceptual change ideas were contextualized to the specific setting of an exploratory lab course. The central change desired was a change of students' framework from one of just doing the lab "cookbook stuff" to engaging in the lab as a vehicle to evaluate the conception models the students had about certain physics ideas. The experiment served as a discrepant event in which the model was evaluated. The whole process was built around the students metacognitively evaluating their understanding of their model. Professor Fairbanks expressed approach was student-centered focusing on the students' framework and individual learning. Yet, ideas regarding students filling knowledge holes and enthused by ideas showed elements of less developed conceptual change categories still present in Professor Fairbanks conceptions. It is important again to note the large differences between PHYS 3000 and PHYS 7050. Notably, it being a lab class and taught to upper-level physics majors. These provided quite a different context and limited the ability to ascertain the extent of the carryover of changes in Professor Fairbanks' conceptions of teaching for conceptual change. With these restraints, Professor Fairbanks' conceptions were interpreted as evolving toward an expert-like view based on his ability to apply his conceptual change framework in designing the physics lab course and setting it goals. However, his conceptions were restricted by the limited conceptual change language expressed and the focus on students filling knowledge gaps.

Language usage.

One characteristic of expertise in a field was the specific language utilized. Generally as one becomes more of an expert in a field, a noticeable shift occurs in the specificity of his or her vocabulary. As detailed, Professor Fairbanks described a general shift in his conceptions of teaching for conceptual change toward a more expert view. To ascertain if an accompanying shift in his vocabulary concerning teaching conceptual change occurred, a word frequency analysis was conducted on all of the interviews. The most frequent words used in each interview were listed using NVivo and then compared and linked to each of the other interviews. From the general terms, specific terms associated with conceptual change were isolated and compared (Appendix L). While the analysis was limited, several general trends suggested a slight shift toward a more specificity in Professor Fairbanks' vocabulary. In the first year's interviews, the *terms*, *ideas* and *misconceptions*, were frequently used. While throughout the remaining interviews the terms associated with ideas continue to be frequently used, the *misconceptions* term was less frequent and the terms of *framework* and *understanding* were more common. The terms of *discussion*, *change*, *connecting*, and *context* appeared more frequently in the second year interviews. Terms of *expert*, *struggle*, *distractors*, and *metacognitive* appeared in the executive interview following the second collaboration. This shifting in frequency from *misconceptions* to *framework* and an increasing emphasis on discussion with associated terms, such as *change*, *connecting*, *context*, and *struggle* reflected the associated shifting of Professor Fairbanks' conceptions of teaching for conceptual change along the category continuum from Students' Learning to Conceptual Change discussed earlier. The analysis interview, following the observations in the upper-level lab class, showed a more frequent use of the terms of *time*, *questions*, and *transmission*. Each of these was associated with constraints that limited Professor Fairbanks' practice of teaching for conceptual change. This suggested limitation on the practice of teaching for conceptual change, which was one of the central findings from the observations of Professor Fairbanks teaching in the upper-level laboratory class.

Summary of physics professor's conceptions of teaching for conceptual change.

Over the two years, a progression was found in Professor Fairbanks' conceptions of conceptual change (Appendix K). This change was linked to his observing Professor Crefeld's instruction and modeling on conceptual change and then his synthesizing many of these ideas into a better conception of the 'logic of teaching'. By the end, Professor Fairbanks' conceptions of teaching for conceptual change moved more toward the expert view in the Conceptual Change category. These changes were supported by an analysis of Professor Fairbanks' language usage (Appendix L). In the next section, the changes in his practice of teaching for conceptual change were closely examined drawing on the classroom observations.

Practices of Teaching for Conceptual Change

Preliminary period.

In the initial interview, Professor Fairbanks expressed a general familiarity with teaching conceptual change from the context of the physics classroom. Observing him in the classroom at the beginning of the collaboration revealed his expressing these ideas in the classroom, but a tension in the modeling of them. The theme of creating a safe environment, where students were comfortable sharing their ideas, was emphasized from the beginning of the first class. The initial focus was aimed at creating an empathy for the struggle the PHYS 7050 students were facing and the need for sharing their ideas or "risk taking". Professor Fairbanks, in his opening remarks, stated, "Physics is hard; teaching physics is hard" and acknowledged his own struggle with his understanding of physics concepts; "PhD in physics and you still have misconceptions". To learn you "have to jump off the ledge", a metaphor for the risk taking of sharing your ideas and being willing to be wrong. (Class 1 Observation, June 5, 2012). Reflecting on this in a journal he kept on his experience of co-teaching PHYS 7050, Professor Fairbanks wrote,

> In my intro to the class I tried to emphasize that they needed to be willing to step out and take a risk and expose their misconceptions, especially since this is what we are trying to get our students to do when we teach. (Professor Fairbanks' Journal Entry, June 5, 2012)

Another early theme from Class 1 was the valuing of students' ideas and their experiential rooting. Professor Fairbanks asked each student to share his or her teaching background and personal experiences with learning physics, drawing out their ideas on learning physics. Later, in the context of asking the PHYS 7050 students to predict their FCI scores, Professor Fairbanks emphasized the importance of the act of expressing the idea over a notion of correctness of the idea, stating "When you ask students to make predictions in the Studio class, their predictions are never wrong. They're just a prediction" (Class 1 Observation, June 5, 2012). The focus switched from the PHYS 7050 students' role as students making predictions to the mindset of them as teachers asking their students to make predictions. This technique, demonstrated here for the first time, of switching the perspective of instruction from the role of the student to the perspective of the teacher became a frequent tool of Professor Fairbanks for highlighting the reasons and motivation behind specific pedagogy.

Student-focused learning and the theme of students' ideas, along with the importance of having them expressed in the classroom, further emerged in Class 3. Following a discussion by Professor Crefeld, the science education professor, on students' preconceptions, Professor Fairbanks interjected his experience about seeing students' misconceptions in electricity even when they have little experience with it. He concluded, "[Students are] always bringing something to a concept even if it is something they just learned" (Class 3 Observation, June 12, 2012). Later, Professor Fairbanks emphasized more student-focused learning, underscoring the need for a teacher to shift students' focus from grades to sharing their thinking. A suggestion by

Professor Fairbanks to help facilitate this was having the instructor sitting down with the students, creating a more direct relationship face to face (Class 3 Observation, June 12, 2012). At the beginning of the following class, Professor Fairbanks reassigned the students into groups of three and rearranged the tables in the room so students would be face-to-face and able to work more closely together (Class 4 Observation, June 14, 2012).

Another theme emerging from the first class was an emphasis from theory to practice. Professor Fairbanks' description of this was "soup to nuts". Reflecting on this in his initial interview, he expounded,

> One of the phrases I used today in class was the class is kind of from soup to nuts as theory to practice here. And spans it and kind of tries to pull those things together. So I'm hoping it will also increase the students' abilities to connect the theory parts that they're going to get with their actual teaching. And they'll see the threads as they go through since we're working hard to kind of weave those together. (Interview, June 5, 2012)

One way this began to emerge was Professor Fairbanks' connecting and drawing on the theory Professor Crefeld was presenting in class. In Class 3, Professor Crefeld presented Posner et al.'s (1982) conceptual change theory and the influence of Thomas Kuhn's (1970) ideas on paradigm shifts. Professor Fairbanks underscored the influence of Kuhn on his own ideas by mentioning that he shared a copy of Kuhn's *The Structure of Scientific Revolutions* with all his new graduate students. In the next class (Class 4) in a discussion on limitations of models, Professor Fairbanks referenced back to Professor Crefeld's discussion on Kuhn, discussing how one of the roles of science was testing models. When discrepancies were found, the models were changed with the older models being discarded (Class 4 Observation, June 14, 2012). Later in Class 4, Professor

Crefeld emphasized the role of dissatisfaction in conceptual change, referencing an article by Hesse (1989). In Class 5, while introducing a lab that the students would be leading in the Studio Physics class, Professor Fairbanks referred back to Professor Crefeld's discussion, adopting the specific vocabulary of "dissatisfaction" and "cognitive dissonance" in discussing the role of students making predictions in the lab. In instructing on the mindset the students should have in leading the lab, Professor Fairbanks emphasized, "We need them [students] to experience that dissatisfaction" but went on to caution that it was not the role for the teacher to tell the student the right answer. (Class 5 Observation, June 19, 2012). The intentionality of this connection was revealed in Professor Fairbanks' journal reflection on Class 4 as he wrote,

> [Professor Crefeld] discussed Hesse article and had really good discussion on bringing about conceptual change. We talked about dissatisfaction, assimilation, etc. This matched up really well with discussion of lab activities and why you do labs. How do we create this dissatisfaction? The discussion from [Professor Crefeld] and I really dove-tailed nicely here. (Professor Fairbanks' Journal Entry, June 14, 2012)

Observing Professor Fairbanks' instruction and his practice in class, a discernable pattern emerged of Professor Fairbanks' instructing the PHYS 7050 students on pedagogical approaches for teaching for conceptual change. In class discussions, Professor Fairbanks' would ask the PHYS 7050 students what they thought their students might be thinking which might conflict with the current concept. In Class 2, Professor Fairbanks instruction began with the students constructing motion diagrams from a worksheet. The students individually worked the first example, discussed it as a class, and then worked with their peers on other examples. In a discussion on acceleration, illustrated by these examples, a challenging issue on visualizing a positive acceleration as a deceleration confused several students. Professor Fairbanks asked the

PHYS 7050 students, "How do you get a student to conceptualize a deceleration as a positive acceleration in the opposite direction of motion?" After discussing it further, Professor Fairbanks led the students in a kinesthetic activity where students moved their fingers to represent the velocity vectors and visualized the positive deceleration. The students then observed a segment of an undergraduate Studio physics class doing the same worksheet on motion diagrams. Afterwards, the PHYS 7050 students shared their thoughts on their observations of the Studio class. Professor Fairbanks emphasized the importance of the students struggling on their own through the concepts and the role of discussion in helping the students' ideas emerge, pointing out one of the biggest challenges for teachers was "resisting temptation to give them answers" (Class 2 Observation, June 7, 2012). Reflecting on his teaching, Professor Fairbanks wrote, "It appears that students are seeing and engaging their misconceptions. Talking about what our students might think and how that would show up is a great way to get the 7050 students engaged in meta-thinking" (Professor Fairbanks' Journal Entry, June 12, 2012).

During discussion and debriefings of activities, Professor Fairbanks would often point out the inconsistencies between the instruction he was sharing and his practice in teaching the physics concepts. During the debriefing of the student-led exercise on motion diagrams in the Studio classroom during Class 2, he commented that the motion diagram worksheet used in both PHYS 7050 and in the Studio class was "not a good design for teacher-student interactions". Near the end of Class 2 in a discussion on a diagram on the same motion-diagram worksheet, Professor Fairbanks remarked this way was probably the opposite of how the students should be instructed to do it (Class 2 Observation, June 7, 2012). This pattern seemed to belie an underlying tension between Professor Fairbanks' views on how students should be instructed to help facilitate conceptual change and the actual choices he made in his own practice.

In this preliminary period, Professor Fairbanks demonstrated a focus on students' ideas, creating an environment that facilitated the sharing of the ideas, connecting the conceptual change theory provided with the science education professor, and instructing and modeling pedagogy on teaching for conceptual change, while identifying at times a tension between his instruction and his modeling. These attributes of his practice placed him between the Students' Ideas and Students' Learning categories, but the teacher-centeredness of his prevalent direct instruction predominated, restricting him more to the Students' Ideas category.

Initial collaboration period.

Professor Fairbanks' classroom practice in teaching for conceptual change, after the first summer of collaboration, largely reflected the emergent practices identified at the beginning of the collaboration. Professor Crefeld's instruction continued to influence not only his ideas, but his practices. A tension remained between Professor Fairbanks' teaching the physics content and his modeling the type of instruction desired for facilitating conceptual change. An illustrative example occurred during the first summer in Class 7 and 8. During these classes, Professor Fairbanks was instructing on circular motion. Identifying centrifugal force as an area where students' experiences often appeared to contradict the physics concept, Professor Fairbanks phrased his response on how to approach students' experiences on centrifugal forces in the terminology Professor Crefeld's emphasized in the conceptual change method of making it intelligible, plausible, and fruitful. Following the class in a private conversation, Professor Fairbanks continued to explore those ideas with Professor Crefeld. Professor Fairbanks identified the tendency in instruction to want to rush past the "students' flawed ideas" and onto the correct ideas of science. He recognized, instead, that more time needed to be given for students to compare their ideas against the new idea, letting them see the plausibility of the new idea. The common practice of predicting and observing was too limiting. Professor Crefeld suggested that a modification was to predict, explain, observe, and then explain (Class 7 Observation, June 26, 2012). Reflecting in his journal Professor Fairbanks wrote,

> I feel a lot of tension between teaching content, modeling the kind of teaching we want them to do, and giving them practice at leading the activity before we do that….I end up doing a speed teaching with too much lecture, but from the questions and body language I sense that they need to start from the beginning. They want to feel solid in their content knowledge going into the activity. (Professor Fairbanks' Journal Entry, June 26, 2012)

In the next class, Professor Fairbanks, with the encouragement of Professor Crefeld, brought up the points of this discussion in his instruction. Identifying the tension between coverage and facilitating conceptual change, Professor Fairbanks stated, "[Professor Crefeld] and I are trying to model how we might do this." He admitted a tendency of "popping into lecture mode" with the idea that this saved time, but in practice it often did not result in the students learning or conceptual change (Class 8 Observation, June 28, 2012).

The tension between teaching for coverage and for conceptual change was markedly visible in Class 10 in Professor Fairbanks' instruction on momentum. His focus, as he stated afterwards, "The 7050 students won't be leading an activity on momentum, but it is important to try and improve content knowledge and pedagogy tool in this area since it is a key one in high school physics" (Professor Fairbanks' Journal Entry, July 5, 2012). He began discussing Newton's 3rd law by drawing the picture of two vehicles of different size colliding on the board. He then solicited students' ideas on what would happen and how the forces on each vehicle would compare. He emphasized the difference in effect on the objects, yet the implication of Newton's 3rd law required the forces to be constant and how Newton's 2nd law explained this. He continued to illustrate this using two blocks pushing on each other and a hand pushing on an object. At the end of this discussion, he looked in Professor Crefeld's direction and stated, "The students have to see it as plausible" (Class 10 Observation, July 5, 2012). To help conceptualize, Professor Fairbanks constructed free body diagrams of the examples on the board emphasizing the vector magnitude. After a break and a conversation with Professor Crefeld, Professor Fairbanks initiated a discussion with the PHYS 7050 students on what things they might see in these diagrams if their own students were doing it and how they would respond to these different issues. At one point in the discussion, Professor Fairbanks emphasized how using the diagrams "will make it intelligible and plausible" (Class 10 Observation, July 5, 2012). In a self-analysis of this, Professor Fairbanks wrote,

> This took a lot of time but it was totally worth it since there were a number of misconceptions that came out and a good discussion of what students might do. It also made very clear how the representations, particularly free body diagrams, help to make inconsistencies more apparent to the students and the teacher. (Professor Fairbanks' Journal Entry, July 5, 2012).

Then Professor Fairbanks began instructing on momentum. Drawing on Newton's 2nd and 3rd Laws just covered, he connected this to the conservation of momentum principle. With the conservation of momentum, he focused on the limitations of its application and how students often over use it in situations where it does not apply. However, all of this was done in a lecture format, with one conservation of momentum problem involving two skaters quickly worked at the end. Recalling afterwards, Professor Fairbanks wrote, "with limited time I opted for some direct instruction to try and give the big picture of momentum" (Professor Fairbanks' Journal Entry, July 5, 2012). Later, reflecting on limitations that he saw in the teaching in the PHYS

7050 course during the first summer, Professor Fairbanks identified this instance of his teaching on momentum.

> Momentum is sort of a big topic and we had a little bit of time and so I didn't feel like I dealt with that very well. Because I went to a bit more of a lecture mode…I wanted them to make sure they saw that, but that is kind of falling back into the old model of just okay just cause they saw it doesn't mean that they got anything from it and I don't know whether they got anything from it. (Interview, July 23, 2012)

As illustrated, the science education professor's co-teaching influenced Professor Fairbanks' teaching. The integration of the specialized vocabulary of conceptual change, the reinforcement of examples of the teaching for conceptual change methodology, the emphasis on 'meta-thinking' by having the PHYS 7050 students discuss the possible initial conceptions of their students and how to approach them all showed this influence. Yet, there was a limitation in the integration of this fully into Professor Fairbanks' teaching. The influence of Professor Crefeld's teaching usually occurred immediately afterwards or in the next class. This suggested some emulating of what Professor Fairbanks heard, but not full assimilation into his thinking and practice, especially in the instances where there was an outside pressure, such as time affecting the instruction. When time pressure was felt, Professor Fairbanks frequently reverted back to a more traditional teacher-centered, transactional teaching method. When questioned or reflecting on this, Professor Fairbanks identified this and exhibited a dissatisfaction with the outcome. However, he did not stay with the newer approaches for teaching for conceptual change under these stressful circumstances. An awareness of Students' Learning and even some aspects of Conceptual Change were visible, but the practice was still very much in the Students' Ideas category, with the emphasis on students' ideas, but through a teacher-centered approach.

Planning period.

The most striking change at the beginning of the second summer semester of PHYS 7050 was the absence of the science education professor, Professor Crefeld. His absence was evident and acknowledged from the beginning by Professor Fairbanks, with a deferring to Professor Crefeld's expertise on teaching for conceptual change and a reluctance to fully engage in instructing on teaching for conceptual change without him.

Similar to the first summer semester, Professor Fairbanks, in the first class, focused on establishing the importance of a safe environment for students to share their ideas and the value of students' ideas. Instructing independently, Professor Fairbanks, modified the order of presenting these themes. Initially, the students were asked to share their teaching background and high school physics experience before the establishing of the importance of providing a safe environment. Without the establishment of the safe environment, the second year students shared less and focused little on the challenge of learning physics.

Following the students' sharing, Professor Fairbanks transitioned into discussing the structure of the class. He succinctly summarized the focus of the class in teaching for conceptual change with the following points: preconceptions – where they come from, understanding where students were and enabling them to understand where they are, let them engage their ideas, and resolve their conflicts. Professor Fairbanks expressed, "I can't do what Dr. Crefeld does" highlighting Professor Crefeld's absence and expertise and Professor Fairbanks' perception of his teaching for conceptual change. After this disclaimer, Professor Fairbanks addressed the first point of students' preconceptions linking them to students' experiences in the world. He stated,

> They [students] come into a physics classroom for the first time and say I don't know any physics. I've never done any physics. Well, they've lived in the world for how many so

> years. No matter what they think they come in with strong ideas of how things work…. It always amazes me that you teach a brand new topic that they haven't had before and they already got ideas of how things should work…. Students don't come in as a blank slate. (Class 1 Observation, June 11, 2013)

As in the previous year's first class, Professor Fairbanks again shared his own personal struggles with physics misconceptions and the challenge of teaching physics concepts. He created an empathy with the MAT students in the challenge that faced them in learning how to teach physics. He shared,

> Just that you know most of the ideas doesn't mean you know how to present them….There were things that I taught certainly in the first two years probably all the time that were not quite right....I didn't have the right conception of how this worked or say the conception of the scientific theory….So everyone's going to have...a lot of alternative ideas and there are some that are very robust and we will learn more about those ideas like force is required for motion. (Class 1 Observation, June 11, 2013)

Professor Fairbanks provided a concrete example to illustrate an alternative idea, "force is required for motion". This pointed to his ability to clearly articulate aspects of conceptual change in a physics context. Professor Fairbanks highlighted the central goal of teaching for conceptual change in the course by stating,

> We have to figure out where they [students] are and help them figure out where they are and get them to engage those ideas if we are going to have a chance to change those ideas or frame them in what we think is the most scientific. (Class 1 Observation, June 11, 2013)

Professor Fairbanks concluded by focusing on establishing a safe environment and modeling it.

> What we want to do and Dr. Crefeld will help do this really well in here is to create an environment here where we are… modeling here what we hope to happen in the classroom…we want to create an environment where students are willing to make mistakes. Because if they are afraid to answer then their ideas which may not be correct will not come out. They never engage them. They never change. They have to be willing to make mistakes, have wrong answers. And so we need to I think undergo that in here...I want you all to be willing to make mistakes. (Class 1 Observation, June 11, 2013)

In Professor Fairbanks' initial framing of the class, a clear view of the framework of teaching for conceptual change was presented with more specific language utilized. However, a self-depreciating tone was noted in his recognition of Professor Crefeld as the real expert. The tension between the ideas Professor Fairbanks expressed and his modeling of them was still present. In describing teaching, Professor Fairbanks stated, "research shows after 15 minutes of lecturing no one is learning anything." This statement followed his own talking for 13 minutes with only one question and brief interjection by a student. Earlier in the class Professor Fairbanks indicated an awareness of this by stating, "We are modeling here what we hope to happen in the classroom over there. Right now we are not because you are all listening and I am doing all the talking" (Class 1 Observation, June 11, 2013).

In the comparison of the first two summer classes of the collaboration, similar themes of creating a safe environment, the importance of students' ideas, and a tension between the instruction and the modeling were seen. In the second year, the framework of conceptual change was more clearly expressed with a much greater emphasis on students' engaging their ideas. The biggest change was Professor Fairbanks instructing independently. In his practice, Professor

Fairbanks' instruction was clearly in the Students' Learning category, but his modeling of the instruction tended toward being more teacher-centered placing it in the Students' Ideas category.

Independent practice period.

Independently teaching at the beginning of the second summer, Professor Fairbanks displayed a hesitation to directly instruct on the theoretical framework of teaching for conceptual framework. As he expressed in his planning interview,

> Professor Crefeld, not being here this first week at all, we're engaging in some of the discussions about that theoretical framework for conceptual change. Although I've learned a lot, I don't feel comfortable enough to be able to actually lead those kinds of discussions. (Interview, June 12, 2013)

He chose to defer the majority of this instruction to Professor Crefeld when he resumed instructing. Professor Fairbanks articulated this in Class 4 by intentionally delaying discussing articles on conceptual change until Professor Crefeld was present. He stated, "We are going to push those [conceptual change articles] off until [we] probably have a chance to do them one time when he [Professor Crefeld] is able to be here" (Class 4 Observation, June 20, 2013).

Due to the very limited time Professor Crefeld was instructing, it became necessary for Professor Fairbanks to incorporate more of the theoretical framework of conceptual change into his instruction. This he approached through concrete examples that he expounded on to illustrate aspects of the theoretical framework of conceptual change. Clear elements of conceptual change theories were evident in his instruction, but only limited development of these elements occurred. Professor Fairbanks' instruction on forces in the third class illustrated this pattern. Professor Fairbanks began,

> We are going to do a little bit on free body diagrams here in acceleration which is a particular difficult concept….They [Students] want to have those things [velocity and acceleration] just match and not have a different idea about what those two things are. So when you have that, how do you know that there is a problem there? (Class 3 Observation, June 18, 2013)

The activity of constructing free body diagrams was "the vehicle" used to begin a discussion on conceptual change. In response to Professor Fairbanks' question, the students only mumbled some responses. Professor Fairbanks continued,

> There has to be something to indicate that there is a mismatch. That there is a problem somewhere. So, when [Professor Crefeld] is here…you are going to have a lot of the conceptual change stuff…he will be looking through some of the literature there on conceptual change and talking about it. (Class 3 Observation, June 18, 2013)

Professor Fairbanks hesitated delving into conceptual change and highlighted that Professor Crefeld would be covering this. Professor Fairbanks persisted in trying to draw out key elements of conceptual change through discussion by further questioning the students. Professor Fairbanks inquired,

> [Professor Fairbanks] When you have two ideas that don't match, what do you have? What is a word for that?
>
> [Student Sandra] Misconceptions?
>
> [Student Lynn] Application of misconceptions
>
> [Student Amy] Alternative
>
> [Professor Fairbanks] Yeah, they are alternative….You are setting up some type of conflict or dissonance…and so now you have something that has to be resolved. We

have these ideas…we may have held for a long time about how things work and include you know about motion, about causes and vocabulary and all those other kind of things….It isn't a framework that is going to change easily. So the thing we will talk more about as we get into some of those articles is okay so what is it that allows us to actually make changes to our ideas. (Class 3 Observation, June 18, 2013)

Professor Fairbanks introduced vocabulary associated with conceptual change, but did not expound on it. Instead, he previewed parts of teaching for conceptual change and deferred more substantive discussion to occur within the structure of an expert whether it be Professor Crefeld or an article. Professor Fairbanks connected the changing of a framework with the specific example of how the idea of forces historically changed from Aristotle to Newton.

[Professor Fairbanks] As we get to the forces area what we have to remember is this, Newton who came along and changed the way people thought for 1000’s of years. Right?

[Student Sandra] We still don't understand it.

[Professor Fairbanks] And it's difficult because so far as it’s natural. Aristotle kind of brought in a natural way of thinking about it where he used logic and not experiment. Whereas Newton and the Renaissance brought in experimentation, right? Rather than just observing nature without any intervention. (Class 3 Observation, June 18, 2013)

A historical, concrete example was used by Professor Fairbanks to illustrate how ideas change. Later in the same class, Professor Fairbanks referred back to the historical example to show the context dependence of ideas and the challenge in classifying ideas.

One of the principles of Newtonian physics is that the changes in the motion of a particular object depends on the forces on that object….We are looking at the motion through the air. The immediate cause of the change in direction has to do with the force on that object in that instant. So there are good reasons why they [students] might want to bring all that stuff in, because in reality... it wouldn't be doing what its doing without those other things happening….They are connecting it when we use that word [force] sometimes with other reasons and situations. Other pieces that maybe are not as relevant. (Class 3 Observation, June 18, 2013)

Throughout this instruction, Professor Fairbanks attempted to engage the students through a moderated class discussion. A few students responded to his questions. He incorporated their responses into his replies, but the discussion was dominated by Professor Fairbanks' instruction with the students' responses being brief interludes.

As the course progressed, Professor Fairbanks continued in his method of instructing on conceptual change from concrete examples as well as persisting in attempting to accomplish this through more open discussions. A discussion in Class 4 centered around a free body diagram of a stationary block on a surface, illustrated by Figure 8.

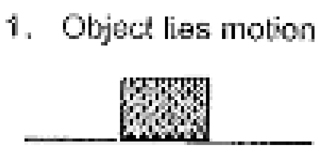


Figure 8. Force Problem Example: Stationary Block on a Surface. Adapted from "Unit IV: Worksheet 1" by J. Saul, *Modeling Workshop Project*, p. 1. Copyright 2002 by University of New Mexico.

Following the drawing of a correct free body diagram on the board and explanation to the class by a student (Ed), Professor Fairbanks posed a question focusing on possible students' preconceptions concerning this situation and facilitated a discussion around this, highlighting the process of conceptual change. Professor Fairbanks inquired,

[Professor Fairbanks] What kind of issues might we anticipate students might do? Anything that might come up there?

[Student Lynn] They might want to put static friction in.

[Professor Fairbanks] They might want to put static friction in and so what would that do to the whole thing?

[Student Bettie] It would give a net force…

[Professor Fairbanks] Where is the inconsistency that we have now?

[Student Amy] There is a net force…

[Professor Fairbanks] We have a net force but no acceleration and that's a problem and if you change this then it doesn't describe the problem you started with. (Class 4 Observation, June 20, 2013)

This discussion prompted a student to express his confusion about the situation which led to a deeper exploration of the underlying ideas.

[Student Ed] I'm confused about if you have a net force in this direction but it's not moving. I don't understand how that affects the acceleration. Like because it doesn't look like the motion is changing, so it doesn't look like there is any acceleration.

[Professor Fairbanks] Yeah, it looks like it should be zero, from the description we know the acceleration should be zero. So that tells us that we should have a net force of zero and our free body diagram should match that. (Class 4 Observation, June 20, 2013)

As the discussion continued, it drew out other students' questions which illuminated additional students' preconceptions, allowing Professor Fairbanks to model the teaching for conceptual change process.

[Student Amy] Can you put F_s [static friction force] in two directions?

[Professor Fairbanks] No, no cause if you have static friction you have one static friction or one for each surface that is touching and you can have multiple if you are sliding along multiple surfaces…So we already have seen that there is going to be a conflict. So what might we do if a student or group put F_s there?

[Student Ed] Ask them to explain it.

[Professor Fairbanks] Okay,

[Student Bettie] Ask them to describe the motion…

[Professor Fairbanks] Okay, so you want to somehow get them to be reflecting on this conflict and noticing that okay there is something inconsistent about what I did. Right? Without just, if we just tell them then there is no F_s then they will just erase it and go on and they didn't learn anything because the next time you ask them they will just do the same thing. (Class 4 Observation, June 20, 2013)

Professor Fairbanks, in addressing the student's question on static friction in two directions did not fully answer it. A student's lingering question, voiced as the repeating of the question about static friction in two directions, pushed the discussion further until another student provided a more satisfying answer that Professor Fairbanks acknowledged and reinforced.

[Student Lynn] What if they put the static friction in both directions?

[Professor Fairbanks] That's right….If we do try and push it in either direction there is F_s so we might think they are both there....Short answer is there can only be one F_s between any two objects…but that is just kind of a memorized answer…

[Student Ed] It has to oppose the motion and there can't be motion in two directions at once.

[Professor Fairbanks] That is right. So the other way of saying it is that static friction opposes the motion that would be there if there wasn't any static friction. (Class 4 Observation, June 20, 2013)

Through this discussion, an emphasis on consistency and on identifying internal inconsistencies in students' ideas was highlighted by Professor Fairbanks. This was consistent with the conceptual change model of creating dissatisfaction with a given idea and the scientific explanation. Professor Fairbanks clearly demonstrated this, but he refrained from using the conceptual change terms. A greater willingness to engage in open discussion was visible. Professor Fairbanks actively repeated students' responses and redirected them as further questions. While some elements of Professor Fairbanks reverting to "expert mode" and directly answering the questions were present, the majority of the discussion was centered around the students' responses, including the concluding statement based on a student's insight.

Professor Fairbanks began incorporating more the terms of conceptual change into his instruction. This progression was demonstrated in a discussion in Class 6. A lab activity to explore Newton's 2nd law using a weighted cart became Professor Fairbanks' instrument to explore how a conceptual change framework informed the writing of pedagogy. In this discussion, Professor Fairbanks' questions elicited from the students an underlying framework and methodology behind the pedagogy of the lab instruction. Professor Fairbanks inquired,

[Professor Fairbanks] How it is written. The kinds of things you are being asked to do. So for instance what is the first thing you are asked to do.

[Student Lynn] Make a prediction.

[Professor Fairbanks] Why do you think we do that?

[Student Sandra] Because it is science.

[Student Bettie] It shows their thoughts and

[Student Sandra] Misconceptions.

[Student Bettie] What they already know.

> [Professor Fairbanks] It shows to who?
>
> [Student Bettie] It shows it to themselves and when someone is walking around, but mostly to themselves and they can know that they can correct it to their own point. You asked them how their results match their prediction.
>
> [Professor Fairbanks] Okay, so we want them to bring out their thinking. They might want to say I don't know what is going to happen. I don't know. But whether they say it or not they do have an idea about what is going to happen….So that is the process. (Class 6 Observation, June 27, 2013)

Professor Fairbanks questioned and prompted the students until they had expressed the central idea. He repeated it for emphasis. Next, he expanded on the idea connecting it with the conceptual change idea of metacognition. He continued,

> Now they don't know why they are being asked to do these things. They don't want to think about why they are being asked to do things. They don't want to be metacognitive. Most of us don't. And so you have to…be prompted to be thinking these things. And you all came to the same mode in a sense that you got into the point of putting these two things in boxes…you had no thought as to why you were asked to put those things in those two boxes, right? (Class 6 Observation, June 27, 2013)

Drawing on the recent experience of the students in performing the exercise, Professor Fairbanks required the students now to switch roles from that of a student to that of an instructor to highlight the necessity of the specific role of the instructor in teaching for conceptual change. He explained,

> And so if guys are not…thinking about why you are being asked to do it. You know that the students are not thinking about why they are being asked to do what they are doing.

> And so that is part which is why you are there as an instructor is to slow them down at times or to prompt them. (Class 6 Observation, June 27, 2013)

In a later interview, Professor Fairbanks described this type of discussion as, "modeling successfully the kind of instruction that we're hoping to see in the classroom itself" (Interview, July 10, 2013). He explained this type of discussion as, "really exploring the ideas, and letting them think through themselves…everyone's participating and I was [asking] kind of short follow up questions to get them to go a little deeper or get them to connect it with something else" (Interview, July 10, 2013).

As the summer progressed, Professor Fairbanks continued to incorporate more open discussions into the class, centering them on concrete examples and using the discussions as a means to highlight more theoretical aspects of conceptual change. His ability to effectively use more open discussions progressed with each class, reflecting his self-assessment, as he stated,

> I'm trying to hold off more on getting in a mode where I'm passing on my great wisdom to students….So keeping those discussions going, and really exploring the ideas, and letting them think through themselves and I think I've gotten a lot better at that actually as the semester has gone on. (Interview, July 10, 2013)

One constant struggle, Professor Fairbanks acknowledged, was a time constraint between his desire to let the ideas come from the students and having the students prepared to physically lead the activity. He summarized his thoughts on this by saying,

> They're [students] going to understand it better and they're going to get more of the idea if you let, it comes out of them and they come to that conclusion and they see how that works than if they're just told that idea. (Interview, July 10, 2013)

He then explained the competing aspect of the class in having the students prepared to teach the activity. He continued,

> It’s not just a theory class. They are actually going in there and doing that….So it isn’t just that I want to get through that material. It’s that I don’t want them walking in feeling unprepared or having an experience where they got to a point and then something they’re kind of lost. (Interview, July 10, 2013)

This conflict was visible in Class 8 as Professor Fairbanks prepared students to lead a spring lab. An earlier class discussion on the lab procedure led to a discussion on the uncertainties of graphs and students’ challenges with them. Professor Fairbanks, checking the time, interrupted a student in midsentence, and informed the class that they needed to prepare to head over to the undergraduate class.

> [Student George] Let's say because of my own combination of myopia and the insufficiency of a meter stick and the spacing of a, of the...
>
> [Professor Fairbanks] We got to, have to move so we'll have to ask questions on the way. (Class 8 Observation, July 9, 2013)

Professor Fairbanks then quickly summarized what the students were to focus on in leading the lab. He stated, “You've got to slow them down and talk through that procedure the same way we did here. Of figuring out is this the right procedure and why, before they actually start making any measurements” (Class 8 Observation, July 9, 2013). Later reflecting on this, Professor Fairbanks described this scene,

> As we were planning to go into this spring lab…[I] wanted to make sure we got through all these points and the things for them to watch for and then it starts to go a little bit

more direct instruction going on there. Because I wanted to make sure that all those points come out. (Interview, July 10, 2013)

So the earlier identified challenge of reverting back to direct instruction, when time pressure was felt, continued and was acknowledged. A tension between the ideas Professor Fairbanks expressed and his modeling of them still persisted.

Overall, a greater understanding of the framework of teaching for conceptual change was seen. Professor Fairbanks used this framework to adapt his teaching methods to a more natural approach of instruction. Beginning with a concrete activity, he progressed via questions and discussions to the underlying theoretical framework of teaching for conceptual change. He sought to make the tacit knowledge of the pedagogy more visible to the students and integrated it into their thinking and instruction. Throughout the summer, a developing of greater skill with confidence in leading and modeling open discussions was demonstrated by Professor Fairbanks, but restrained by perceived time pressure and competing interests. These findings indicated a progression in Professor Fairbanks' practice of teaching for conceptual change to the Students' Learning category with some elements of the Conceptual Change category present.

Resumed collaboration period.

After independently teaching the class during the second summer semester, Professor Fairbanks resumed collaboratively teaching the course with Professor Crefeld starting with the ninth class. Several distinctive differences were immediately apparent in the collaborative classroom. Mutual respect and collegiality were exhibited between the two instructors. For example, Professor Crefeld in his opening remarks of his first class summarized the collaboration, emphasizing the positive experience it had been.

> So last year we had the wonderful opportunity to co-teach the class which we had every intention of doing this summer except my schedule got filled up…for July at least I have the opportunity to come in a few times and talk to you and to rekindle the magic of last summer. (Class 9 Observation, July 16, 2013)

While Professor Crefeld was addressing the classroom, Professor Fairbanks was sitting next to him at the front of the room. In response to Professor Crefeld's remark, "rekindle the magic," Professor Fairbanks visibly smiled (Class 9 Observation, July 16, 2013).

Furthermore, each professor linked his instruction to each other. Professor Crefeld referenced specific physics examples of Professor Fairbanks' instruction to illustrate the theoretical concepts he was teaching. In his first instruction of the second summer (Class 9), Professor Crefeld began his instruction, illustrating the idea of a concept by referring to force and using the physical prop of a force worksheet Professor Fairbanks had recently worked through with the students. Professor Crefeld explained,

> A concept is an abstraction….And the reason I picked this [picks up a force packet and points toward it] is because here is a beautiful example, force. Students conception of force, concept of force, is often not the same as science's concept of force. (Class 9 Observation, July 16, 2013)

Professor Crefeld targeted prior instruction of Professor Fairbanks on forces to illustrate the idea of a scientific concept. Referencing a prior assessment (Appendix H) given by Professor Fairbanks, Professor Crefeld continued, "You were given a teacher's strategy form...a particular scenario from a classroom where there was a discussion in a physics class about force and there was a transcript [looking around the room with a puzzled look on his face]. I am looking at kind of strange stares" (Class 9 Observation, July 16, 2013). After the students exhibited confusion regarding this, Professor Fairbanks interjected, “You did this in the first week” (Class 9 Observation, July 16, 2013). Despite Professor Crefeld’s prior absence from the classroom, he had a clear understanding of what Professor Fairbanks covered, demonstrating the nature of collaboration between the two instructors.

This collaboration was further shown by Professor Fairbanks in turn linking his specific physics instruction to the theoretical ideas and pedagogical methods Professor Crefeld had just covered. For example, following Professor Crefeld’s instruction in Class 9 on discrepant events, Professor Fairbanks previewed the next class and the use of physics simulations. Gesturing toward the board, where a diagram and description of Professor Crefeld’s demonstration was still visible, Professor Fairbanks connected the simulation with a discrepant event. He stated,

> We have been talking about a discrepant event and so you will see the way this is laid out as you go through. Where you do a lot of making predictions before you actually do the simulation. And you can get the idea that may cause some discrepent events that they [students] are going to be able to look at and try to have to resolve. (Class 9 Observation, July 16, 2013)

This transition, linking to the previous instruction, was a consistent pattern utilized by both professors to provide a continuity to the class with the separate segments of instruction.

Throughout Professor Crefeld’s instruction, Professor Fairbanks periodically interjected, engaged in side conversations with Professor Crefeld while students were working, and answered questions directed at him by Professor Crefeld. These interactions illustrated aspects of the collaboration and the active engagement of Professor Fairbanks. An episode in Class 9 illustrated this. Discussing the challenges of understanding the concept of heat, Professor Crefeld shared an example from a recent workshop of how physics and chemistry teachers when asked to define heat and temperature defined it differently. Addressing one student's question on how the chemists defined it, Professor Crefeld stated, "They [chemists] define it more in term of a thing…physics teachers make a big deal of heat as a process and so that is really a key part, right! Professor Fairbanks interjected, "And we know who is right." To which the class responded with laughter (Class 9 Observation, July 16, 2013). Professor Fairbanks used humor to underscore Professor Crefeld's point and then reinforced it with his own experience. Professor Fairbanks continued, "I was saying…most physics majors don't get a reasonable model for temperature" (Class 9 Observation, July 16, 2013). This prompted Professor Crefeld to share about a book that provided a historical context for understanding heat. Professor Fairbanks responded sharing a historical anecdote about Count Rumford he had used in his classes to explain how our modern understanding of heat developed (Class 9 Observation, July 16, 2013). This side conversation between the two professors, where they offered examples of helpful resources, personified a collegiality that was apparent throughout the co-teaching.

In his initial instruction, Professor Crefeld modeled and instructed on the pedagogy of a moderated class discussion in which he solicited students' ideas, reinforced the key ideas, guided the conversation to establish connections between the ideas, and provided instruction expanding the ideas making explicit tacit knowledge behind the pedagogy he was exploring. Professor Crefeld began his instruction by sharing a prompt with the students, having them write their ideas down in a notebook. He inquired, "What is it that we fundamentally do as science teachers with our students? What are we trying to accomplish with our students? This is not a rhetorical question. I want you to ponder upon it…write a response to that prompt" (Class 9 Observation, July 16, 2013). He then asked each student to share his or her key idea which he wrote on the board and verbally summarized, reinforcing the key points. One student (Ed) expressed confusion about the question, stating, “So I was struggling with this question because I thought there was an answer you were looking for and I thought about [it]. And I realized that maybe it didn't matter” (Class 9 Observation, July 16, 2013). Professor Crefeld responded by repeating the students’ response and then using it to instruct on the mindset of teachers during discussions. He responded,

> So Ed started off by saying, I thought you were looking for one answer. Alright and that is very important. The mindset with which students go into something that we are doing with them…as a teacher I should check on that. (Class 9 Observation, July 16, 2013)

Professor Crefeld established connections between the students’ expressed ideas and the pedagogy he was demonstrating. He further expanded on the ideas behind the pedagogy where he specifically discussed his thought process. He utilized the pedagogy of class discussion, intentionally making explicit the tacit knowledge of the instructor. Professor Crefeld elaborated,

> So this is an important thing, about engaging students in small group discussions like this, is that as the teacher you monitor those discussions. So for instance I heard Ed say something which I wanted to come out in this discussion and I was not sure if it will come out. So if it doesn't come out when the other two groups talk then I am going to make sure to go back and ask him to share his idea. So monitoring those discussions and thinking about how when you talk with the students you get them to share their ideas and how you can build off them is a very effective means of making those discussions meaningful. (Class 9 Observation, July 16, 2013)

Professor Fairbanks actively observed all of Professor Crefeld’s modeling of a moderated class discussion. Professor Fairbanks noted later,

> He's [Professor Crefeld] very good at being able to do that [model instruction] and very comfortable in leading those kinds of discussions and he talked a little bit more explicitly actually this time about what he's trying to do and how it works when he was trying to lead those kinds of discussions. (Interview, July 31, 2013)

Professor Fairbanks, having attempted to emulate the approach Professor Crefeld modeled the first summer, was more focused and receptive when Professor Crefeld began instructing and modeling teaching for conceptual change during the second summer. Following Professor Crefeld's initial instruction, modeling and instructing on the pedagogy of a moderated class discussion, Professor Fairbanks led a discussion on momentum. Momentum was the one topic Professor Fairbanks identified from the first year as not being taught very effectively. "The momentum stuff we did last year didn't work very well" (Interview, July 10, 2013). He cited, "we covered it in too didactic of a way" (Interview, June 12, 2013).

This year Professor Fairbanks delivered his instruction on momentum as a moderated class discussion, differing in many key ways from his earlier didactic instruction. Many of the differences resembled the forms of instruction he had just observed from Professor Crefeld.

Professor Fairbanks began his instruction on momentum by asking an open-ended question on the students' knowledge of momentum as he stood by the board to write down key phrases from the students' responses. He began,

> What do you know about momentum?
>
> [Student Loretta] It's kind of related to like Newton's Laws. The third law about how different things stay in motion. [Professor Fairbanks writes on the board with his back toward the students 'things keep momentum']
>
> [Professor Fairbanks] Okay.

[Student Amy] It cannot be lost or destroyed just transferred.

[Student Lynn] What goes in comes out.

[Professor Fairbanks] Now Newton's 3rd law you said ‘things in motion?’

[Student Lynn] Well, I think the whole law is things that stay at rest tend to stay at rest and things that are in motion stay in motion or something to that effect.

[Professor Fairbanks] Okay, [writes below earlier phrase ‘Newton’s third law’ on the board with the word ‘tendency’ below] and then you said something about not being created or destroyed.

[Student Amy] Only transferred. [Professor Fairbanks writes ‘not created or destroyed only transferred’ on board.]

[Student Lynn] Interactions do not change the systems total momentum

[Professor Fairbanks] Okay. So this is something about a conservation law. Right. [He writes conservation law at the bottom of the board] Okay. [Professor Fairbanks turns and faces the class]. (Class 9 Observation, July 16, 2013)

In this conversation, Professor Fairbanks focused on capturing the key phrases of the students’ responses and writing them on the board. He did not immediately correct an obvious wrong answer of the misidentified Newton’s 1st Law. He used his summarizing of the points to further refine the ideas and prompt the students to expand on their ideas (e.g. supplying the phrase ‘conservation law’ to describe ‘not created or destroyed only transferred’). A major difference from Professor Crefeld’s soliciting of student ideas and in Professor Fairbanks’ practice was the absence of students writing their ideas down prior to sharing – a purposeful period of metacognition.

Continuing the discussion after identifying a conservation law, Professor Fairbanks solicited further students' ideas about momentum.

> [Professor Fairbanks] Any other things you think are important about momentum?
>
> [Student Loretta] One other question…Is it the change in momentum that is the impulse or like if you want to change the...
>
> [Professor Fairbanks] So we have this idea of impulse here too [writes 'Impulse' near the top of the board] that we need to figure out what that is and how that is connected to this idea of momentum. How do you think? Well anything else you want to bring up as important?
>
> [Student Ed] In the book they emphasize the model of the system that you use when you are talking about momentum
>
> [Professor Fairbanks] Okay, let me write it down here. Something about the system is important…
>
> [Student Lynn] Yeah, the system's total momentum stays the same throughout the interaction.
>
> [Professor Fairbanks] Okay. So let's, [steps away from the board and looks back at the list he's written] contrast this to energy. Another thing we have a conservation law about. So we will go back there. What is similar? What is different about when we think about energy? (Class 9 Observation, July 16, 2013)

Professor Fairbanks summarized the student's question about impulse, but did not directly answer it. He sought additional students' ideas on momentum without directly confirming the student's statement on the connections with momentum. He then provided a redirection, guiding the students to compare the similarities of momentum and energy. As the discussion continued, Professor Fairbanks had the students evaluate each of the ideas written on the board in regards to energy. During this exchange, a student brought up mass as a difference between momentum and energy.

> [Student Sandra] Momentum depends on mass and energy doesn't [it]. Is that possibly a concept? [Professor Fairbanks writes "-mass" in the momentum category and writes "mass?" in the energy category]
>
> [Student Ed] I thought mass is energy?
>
> [Student Sandra] Okay.
>
> [Professor Fairbanks] Okay. [writes "mass is energy" under the energy category]
>
> [Student Lynn] Can you tell us the answers. (Class 9 Observation, July 16, 2013)

Professor Fairbanks did not directly answer the student's question, but instead identified the key idea of the question, allowing the students to wrestle with the ambiguity. Lynn's direct request for Professor Fairbanks to give the answers suggested a discomfort with the ambiguity, implying this was an unfamiliar place for her, different from past classroom discussions.

Continuing the discussion, Professor Fairbanks revisited the earlier misidentified Newton's 1st Law.

> [Professor Fairbanks] What was it you said Newton's - the statement was things in motion stay in motion and which of Newton's laws was that?
>
> [Student Loretta] The third wasn't it.
>
> [Student Sandra] Oh no.
>
> [Student Amy] I don't think so.
>
> [Student Loretta] The third isn't it.[Professor Fairbanks erased third]

[Student Sandra] The second one. [Professor Fairbanks wrote first in erased space on board]

[Student Loretta] The third is the...

[Student Sandra] Yeah.

[Professor Fairbanks] It is the first law. Things in motion stay in motion.

[Student Loretta] Aw, just kidding.

[Professor Fairbanks]Things in motion stay in motion….So how does this [points at Newton's first law on board] have to do with momentum?

[Student Sandra] Its keeping momentum, the same momentum, right?

[Student Amy] Unless a force

[Professor Fairbanks] It has a tendency here so unless acted on by a force. So that means it has something to do with momentum. That is good. [draws an arrow from momentum down to tendency on board] So this has something to do with this or with this, right. [then draws a branched line from Newton's first law up to momentum and other branch down to created or destroyed].

[Students] Right.

[Professor Fairbanks] So somehow we have to figure out, how does that tendency of things to keep doing what they are doing show up in terms of momentum. (Class 9 Observation, July 16, 2013)

Professor Fairbanks addressed the misidentified Newton's Law, giving the students the opportunity to recognize the mistake before correcting it. Students' confusion on Newton's Laws was apparent and Professor Fairbanks addressed this by restating the laws and focusing the discussion on identifying the connection between Newton's 1st Law and momentum. Having focused the discussion, Professor Fairbanks pushed the students to attempt to provide the connections between the ideas prior to his providing them. He challenged the students, pushing them to further clarify their ideas, revealing underlying confusion in their understanding and directing them to the key idea of defining the system. He stated,

> [Professor Fairbanks] Forces can do something. So a force acting on an object what happens to its momentum?
>
> [Students] It changes.
>
> [Professor Fairbanks] So it can change, so I'm confused because I thought momentum was conserved.
>
> [Student Ed] It is within the system..
>
> [Student Lynn] The conservation is within the system not, not in just one unit.
>
> [Professor Fairbanks] The system is the ball.
>
> [Student Ed] Your system is the ball?
>
> [Professor Fairbanks] Yeah.
>
> [Student Ed] So if you are thinking about all the particles that make up the ball all the momentum of those particles kind of cancel each other out. Like each particle has its own momentum, but they all kind of cancel out unless there is some kind of outside force like the ball hitting the wall…
>
> [Professor Fairbanks] So how it that connected. How do we connect that and momentum. In this whole [simulates hitting a baseball] say we pitch a ball and we hit it [swings and follows through].

[Student Ed] Well, I 'm looking at it two different ways. If the ball is itself is the system that you are talking about then the total momentum of this ball. Nothing happening to it then the momentum is

[Student Amy] In equilibrium, right.

[Student Ed] In equilibrium. All the ball, even though each particle that makes up the ball has its own momentum, but it kind of cancels out to…it's in equilibrium. It's not doing anything, but if you have an impulse coming from the outside of the system. Like the bat that changes the momentum.

[Professor Fairbanks] So you are putting the forces somehow into forces within the ball and forces from the outside [draws two arrows from force on the board one to ball and one to outside].

[Student Ed] Yeah.

[Professor Fairbanks] Is that what you are doing?

[Student Sandra] Net force.

[Professor Fairbanks] Okay, okay. So actually we will label these maybe internal and external [writes internal by ball and external by outside] with respect to what? How do we determine what is internal and what is external?

[Student Loretta] We have to determine what is our system.

[Professor Fairbanks] Ah. Okay. That is good, very good. But that is going to determine what is internal and what is external is what is our system. (Class 9 Observation, July 16, 2013)

Professor Fairbanks continued to focus the discussion, pushing the students to extend the idea of a system to a common application (two pool balls) - going from the theoretical concept to a concrete example. He provided key vocabulary for the ideas students have supplied and pushed them to further refine these ideas. He challenged the students to identify an actual system which illustrated these concepts.

> [Professor Fairbanks] So are there circumstances in which we can have a system smaller than the universe where momentum is conserved.
>
> [Student Ed] Yes.
>
> [Student Amy] Yeah.
>
> [Professor Fairbanks] Okay like what kind of?
>
> [Student Ed] Like a ball.
>
> [Professor Fairbanks] Like a ball that we are not doing anything.
>
> [Student Ed] Yeah.
>
> [Professor Fairbanks] [picks up coffee thermos and places prominently on table] Okay, anything more interesting than that where momentum is conserved...
>
> [Student Sandra] Someone swimming in a pool. Is that strange, I don't know.
>
> [Professor Fairbanks] A pool might be a good example. Getting out of a pool might be good.
>
> [Student Ed] Oh, like a pool ball.
>
> [Professor Fairbanks] Aw, okay. These are situations that we might be able to have. So why might we have, want, let's say we have two pool balls colliding. Is it possible momentum is conserved in that? (Class 9 Observation, July 16, 2013)

Once the key connections were established, Professor Fairbanks reinforced these key ideas as illustrated below in the connection between internal forces and net force on a system.

[Professor Fairbanks] So the weight and the normal forces you think generally they are going to be canceling each other out. So they are not providing any net force to the two balls. What do you know about the force of one ball on the other and the force of the second back on the first?

[Students] Equal and opposite.

[Professor Fairbanks] What about the net? So when you group those two things together as a system

[Student Amy] The total net force is zero.

[Professor Fairbanks] The net force from an internal force to my system is always going to be zero. (Class 9 Observation, July 16, 2013)

Having established the key connections through the guided discussion, Professor Fairbanks summarized the discussion and then began to further instruct on the ideas. While still prompting the students, he transitioned into a more direct teaching method.

[Professor Fairbanks] So we are talking about the forces between the two balls and we moved into the general idea of two things interacting with each other. And now so we have extended it a little bit to talking about two things of different mass….We want to have the idea that the more massive object applies a bigger force to the lighter object that is our first thought. Because we know that the effect is different. Right.

[Student Amy] Like the big school bus applies a much greater force than the Honda Civic.

[Professor Fairbanks] But Newton's third law, right. So now we are moving into Newton's third law here.

[Student Sandra] So it is an equal force?

> [Professor Fairbanks] Newton's third law says an equal and opposite….Newton's third law is the thing that tells us we don't have to be concerned about internal forces because they are always equal and opposite….A system cannot apply a net force to itself. (Class 9 Observation, July 16, 2013)

Professor Fairbanks concluded the discussion on momentum by directly instructing on students' difficulties with conservation laws, making visible common students' thinking on conservation laws. He explained, "Students either want to use the conservation law all the time or not at all….They will want to jump to the end and apply a conservation law. And the question we have to ask is…when are they conserved? (Class 9 Observation, July 16, 2013)

Throughout the momentum discussion, Professor Fairbanks solicited students' ideas, refined the ideas guiding them to key ideas of momentum, reinforcing central characteristics of momentum and then provided additional instruction. A marked difference in Professor Fairbanks' approach was evident when he let the students do the work of trying to provide connections between the ideas instead of providing the connections for them. His role was guiding the students toward the connections and challenging their ideas with a focus on their developing a conceptual framework about momentum.

Many similarities were noted between this momentum discussion and the earlier one in class led by Professor Crefeld. Both began with questions seeking students' ideas. Students were encouraged to share their ideas which were summarized in written form and repeated back. The ideas were further refined through questioning and more students' input. The discussion was guided to establish connections between the ideas, and these connections were reinforced by the professor's instruction. In their instruction, both professors were explicit about underlying thinking and tacit knowledge that influenced students' understanding of the concept.

Key differences were noted in the momentum discussion and prior discussions led by Professor Fairbanks. Students' ideas were acknowledged but not immediately confirmed. This included not correcting obvious errors or immediately answering students' questions. Students were challenged to make the connections between the ideas with the guidance of the instructor. Direct instruction was minimized and only utilized after the key ideas and connections had been identified. While aspects of this type of discussion have been displayed previously, no prior moderated class discussion focused as intensely on the students' ideas with the students connecting their ideas into a coherent framework of the concept.

Moderated class discussions led by Professor Fairbanks continued in subsequent classes with some of the same characteristics, but were not as intentional or developed as the momentum discussion. In Class 12, talking through the possible responses to FCI questions, Professor Fairbanks led an impromptu discussion on buoyancy, centered on an example of a pen surrounded by air. In this discussion, students' ideas were again solicited. Professor Fairbanks challenged these ideas through the discrepant event of the buoyancy of a pen as he pushed the students toward connecting their ideas into a coherent framework on buoyancy.

> [Professor Fairbanks] Is there any air force on that pen right now? [Holds a pen in the air in front of the class.]
>
> [Student Amy] No
>
> [Student Ed] In all directions...
>
> [Student Sandra] There's no motion.
>
> [Professor Fairbanks] Is it the same in all sides?
>
> [Students] Yeah.
>
> [Student Ed] No

[Professor Fairbanks] Now see you are trying to guess what I am thinking... (Class 12 Observation, July 23, 2013)

Clearly seeing students were confused in their answers, with a wide range of preconceptions, Professor Fairbanks proposed a scenario of placing the pen in water and asking the students what would be the net force due to the water. More confusion prompted him to modify the scenario, comparing a pen made of wood with one made of metal.

[Professor Fairbanks] If this was made of wood and I put it in the water would there be a buoyant force?

[Students] Yeah, correct.

[Professor Fairbanks] If it is made of metal and I put it in water is there a buoyant force?

[Students] Yes. Yeah.

[Student Amy] But it's not.

[Student Lynn] It's not big enough.

[Professor Fairbanks] But its smaller...because the buoyant force depends on what?

[Student Sandra] Only on the density or weight or something like that?

[Professor Fairbanks] How much what? How do I determine how much buoyant force there is? The density of what?

[Student Amy] Of the object.

[Professor Fairbanks] Of the object? So there's. If I had two identical objects in shape a wood one and a metal one and I put them in water then which one has more force…buoyant force?

[Student Sandra] The wood.

[Professor Fairbanks] The wood has more buoyant force than the metal and why is that? How does the water know that its made of metal and not wood?

[Student Lynn] The density.

[Professor Fairbanks] How does the water know the density of the thing?

[Student Loretta] Because the way it interacts.

[Student Amy] It has a greater mass so which allows it to have a greater force that lets it go through the water.

[Professor Fairbanks] For instance let's take the same object both are made of metal but one is hollow and I put it in there. Which one has a bigger buoyant force?

[Student Loretta] The one that falls. (Class 12 Observation, July 23, 2013)

Professor Fairbanks used the scenario of the pen to set up a discrepant event challenging the students' ideas on buoyancy. Throughout the discussion, students' were expressing preconceptions even when they were obviously contradictory to the scenario discussed. Professor Fairbanks, having illustrated the idea of buoyancy in the more familiar context of water, then returned to the original less familiar context of buoyancy in the air, replacing the pen with a more common example of a helium balloon.

[Professor Fairbanks] So if I take an object and I put it in the air. Right. Then I am going to displace some air and I am going to get forces on it on each side. And is there going to be a net force?

[Student Ed] No.

[Professor Fairbanks] Now I am taking an object and putting it in the air. I've just displaced. Do you see this air here?

[Student Amy] But there is less air on the bottom than on the top.

[Professor Fairbanks] Less air? Where is the pressure higher?

[Student Loretta] The air pressure is equal.

[Professor Fairbanks] The pressure is higher.

[Student Amy] I'm sorry, its below

[Student Sandra] It's such a small amount.

[Professor Fairbanks] Is it as high here than it is here?

[Students] Yeah.

[Professor Fairbanks] So is there a buoyant force? Is there a net force on it?

[Student Sandra] No

[Professor Fairbanks] Okay. Let me take a helium balloon and put it here.

[Student Amy] Well, there it goes up.

[Student Loretta] It’s going to go up.

[Professor Fairbanks] Okay, why?

[Student Amy] Because it is less dense.

[Student Sandra] The pressure is more on the bottom.

[Professor Fairbanks] It’s less dense. It is displacing air and the pressure is larger on one side than the other so there is a net force.

[Student Sandra] That is tricky.

[Professor Fairbanks] Right so, a helium balloon is less dense than air and therefore it floats….So that was definitely true for a helium balloon. Is it true for this when I put this here [Holds pen in the air again]? (Class 12 Observation, July 23, 2013)

Throughout this discussion, the emphasis was on drawing out students’ preconceptions and challenging the students to connect their ideas in a coherent framework. Again, Professor

Fairbanks did not initially correct students' inconsistent ideas, but instead asked questions that exposed the inconsistencies. Unlike in the momentum discussion, Professor Fairbanks did not intentionally write down the students' ideas on the board and summarize them. Yet, he did challenge the ideas through a series of questions posed around an extemporaneous scenario. An implied expectation was that the students' ideas should connect in a framework which was consistent across different contexts (water, air, different densities, etc.) - characteristics of teaching for conceptual change. The discussion pattern of soliciting students' ideas, having students evaluate their ideas in light of a specific context, emphasizing key points, and instructing to expand the ideas resembled the momentum discussion. One of the big differences in this buoyance discussion was its extemporaneous nature, unlike the intentionality behind the momentum discussion. Buoyancy was not a topic in the syllabus and not one taught last year. Professor Fairbanks, resorting to this type of moderated discussion, focused on conceptual change without prior planning was significant. It implied an internalization of the conceptions of teaching for conceptual change and a greater confidence in implementing them.

In the buoyancy discussion, Professor Fairbanks led the students in the exploration of buoyancy in different contexts. Students expressed different ideas depending on the context, such as the wooden pen would have a buoyancy force on it, but a metal one would not. Professor Fairbanks pushed them to connect their ideas, forming a logical framework. The context dependence of these ideas was a theme that continued to emerge in Professor Fairbanks instruction. As Professor Fairbanks discussed the FCI and reasons why students would chose different answers, he developed scenarios where students combined preconceptions to form what appears to them a logical framework supporting the incorrect answer. He explained,

> If they [students] have this idea…that motion requires force and the bigger the force the faster it moves ….Then in their mind they might think well then that means that the force must be increasing. And then they hear over here that the gravitational force depends on how far we are from the center of the earth. Well, that connects really well. That tells me that as we move, as we go down the force is getting bigger and that is why it is speeding up. So they can develop a pretty consistent and pretty incorrect picture of what is going on because of this combination of these misconceptions. (Class 12 Observation, July 23, 2013)

As he concluded Class 12, Professor Fairbanks stated, "They [students] can have pretty good ideas and still get some of these wrong because they are connecting it to a certain kind of experience" (Class 12 Observation, July 23, 2013). Professor Fairbanks distinguished between students' ideas and misconceptions showing that the students' ideas have validity as they were based on experiences. He was beginning to articulate how students' associate their ideas with particular experiences and what students were not recognizing. This was the context dependency of these experience-based ideas which can lead to an incorrect framework.

In the next class (Class 13), Professor Fairbanks articulated his developing ideas on how students form incorrect frameworks from misconstruing context-dependent ideas. In a side conversation with Professor Crefeld, recapping the previous class and the results of talking through the FCI responses Professor Fairbanks stated,

> You get these misconceptions that form a framework, but stable framework actually. For instance…air pressure to most people. Air pressure is pushing down on stuff. It's one reason that things drop....And the ideas that they know that they connect with some of the other points. The other ideas that the force of gravity is weaker as well, which it is going

> down. They connect that with the idea that force is required for motion and then of course you get velocity. Then they connect with the idea that when they speed up. So they have a misconception that they've connected that forms you know the incorrect mixing up result...So some of the distractors are actually kind of complicated, alternative conceptions connected....It's not just one idea. Its how it connects with other ideas. Except it is difficult for them to change from having the right conception in one picture and then they have a different type of question that they understand perfectly well, suddenly incorrect. (Class 13 Observation, July 25, 2013)

Professor Fairbanks repeated the connections he made in the previous class on gravity, force, and velocity. He added the idea of air pressure which was at the center of the buoyancy discussion to the scenario of interconnected ideas leading to an incorrect framework. While he did not specifically articulate context-dependent ideas, his assertion of students having the right conception in one problem, changing the picture slightly, and then getting it wrong pointed to his understanding of this. Later in the same class, Professor Fairbanks expressed these ideas to the students as he resumed talking through the FCI responses,

> What we will see is that as we go through here are misconceptions. They are not simple a lot of times. There are connected ideas and even if you can have say a question which is a Newton's 3rd law question. You can in one question. You can answer perfectly well. Be very confident that you know what is the right answer. And then in another circumstance maybe not. Right. So it is not like the idea once you have it, you have it. It's the way you think about situations for all these different situations. You know what idea you're bringing. What other ideas are interacting with it. These ideas aren't in isolation. (Class 13 Observation, July 25, 2013)

Professor Fairbanks expressed more clearly the interconnectedness of ideas and that the idea must be understood in a variety of contexts. Further, he referenced the tacit knowledge of an expert in knowing in which situations to activate certain ideas. Professor Fairbanks continued this by leading discussions on FCI questions to understand the expert conception in the specific context of the question. He described the process as, "You present the expert conception on the concept. So now we are trying to close that loop by working through and looking through answers and understanding what is the framework we are actually trying to work towards" (Class 13 Observation, July 25, 2013).

A progression was seen in Professor Fairbanks' expressing the conception of teaching for conceptual change as dealing with context-dependent ideas forming frameworks. In another discussion, Professor Fairbanks modeled this process of teaching for conceptual change by understanding the expert framework as it related to Newton's 3rd law and a car pushing a truck while speeding up.

> [Professor Fairbanks] So the car is speeding up and pushing the truck. So what is true about the forces between the two?
>
> [Student Amy] Equal but opposite.
>
> [Professor Fairbanks] Okay.
>
> [Student Lynn] Still? When they are speeding up?
>
> [Student Sandra] Well, that is what I thought.
>
> [Student Lynn] Well, that is where I got tripped up. I was thinking well if they are both going at a constant speed then it's equal but opposite. If they are accelerating then one force is going to be bigger than the other.

[Professor Fairbanks] Okay. So we can go back and look at Newton's 3rd law which says what?

[Student Amy] For every action there is an equal and opposite reaction.

[Professor Fairbanks] Reactions, except when?

[Student Loretta] Except?

[Professor Fairbanks] I guess there is no exceptions. Right. No matter if they are speeding up or slowing down and it's actually Newton's 3rd law is really a fundamental thing….So Newton's 3rd law says we don't really like that idea. We don't always buy it. That a car can apply a force to the truck once the truck applies a force back to the car. So we've got to separate that from what makes something speed up. (Class 13 Observation, July 25, 2013)

Professor Fairbanks demonstrated the expert's understanding of Newton's 3rd law that there were no exceptions to it. So when given the distractor of an acceleration taking place, which implies a net force, the expert was still able to separate out the interactions which were due to Newton's 3rd law. Professor Fairbanks continued to explore this scenario, transitioning from probing the students' understanding with questions to explaining through more direct instruction. He summarized the central challenge, "Students who if you ask them what Newton's 3rd law is and they can recite it in a second. Right. But actually believing that it is true and applying it to a situation is a whole different thing" (Class 13 Observation, July 25, 2013).

Following Professor Fairbanks in the last class, Professor Crefeld summarized the principles Professor Fairbanks had begun to articulate and model in his advice for teaching for conceptual change. He stated, "True conceptual change takes time. Requires exploring phenomenon in multiple context" (Class 13 Observation, July 25, 2013).

In the resumed collaborative instruction with Professor Crefeld, many changes were noted with Professor Fairbanks' practice. The collaborative element modified the class format. Each professor instructed during the same class. Professor Fairbanks actively engaged in learning during Professor Crefeld's teaching. Professor Fairbanks reflected, "So it [Professor Crefeld's instruction] matched up with what I was experiencing and how I was, you know, struggling". He also was actively involved, providing input into discussions, engaging Professor Crefeld in side conversations on the topics taught, and referencing Professor Crefeld's instruction in his own teaching. Professor Fairbanks exhibited significant differences in the way he conducted class discussions from the past. Noted changes included a stronger emphasis on soliciting students' ideas, guiding the conversation to establish connections between these ideas, refining the ideas through further students' input, and only engaging in direct instruction at the end to make explicit underlying thinking and tacit knowledge. All of these traits were characteristic of Professor Crefeld's initially modeled classroom discussion. Professor Fairbanks' adopted use of writing students' ideas on the board strongly resembled Professor Crefeld's technique. However, this method was not found in subsequent classroom discussions led by Professor Fairbanks, suggesting an emulation of Professor Crefeld. In contrast, the changes in Professor Fairbanks soliciting students' ideas and guiding the students to connect and refine ideas were observed in following discussions, suggesting more assimilation into his teaching practice. The development of Professor Fairbanks' ideas about context-dependent ideas forming stable frameworks was evidenced through the last couple of classes and showed the continued evolution of Professor Fairbanks' framework of teaching for conceptual change.

With these changes Professor Fairbanks showed progression in the conceptual change category continuum from Students' Learning to Conceptual Change. Key points in this included his focus shifting from changing students' ideas to establishing the connection between the ideas and focusing on changing students' frameworks. There was emphasis on exploring ideas in a variety of contexts as shown in the buoyance discussion. Many ideas expressed earlier, but not exhibited in his practice, became visible in his teaching especially in his moderated class discussions. Professor Fairbanks significantly shifted to student-centered discussions while restraining from directly answering questions and providing connections. Students were challenged to evaluate their ideas in light of a discrepant event and connect their ideas into a logical framework. This was strongly influenced by Professor Crefeld's modeling and instruction. Limitations were still evident in Professor Fairbanks' practice, signifying he was more novice than expert. These included acknowledging but not emphasizing metacognition of the students and a continued challenge of integrating a consistent framework of teaching for conceptual change throughout his instruction.

Extended practice period.

Professor Fairbanks was observed teaching two classes in PHYS 3000 to two different sections. In both classes his goal was "to set the foundation for five experiments in one class period" (Interview, October 9, 2013). This goal denotes a focus on providing a background for a semester of lab work. This was a very different aim from PHYS 7050's focus on teaching physics content for conceptual change. These contrasting aims are important to note and consider in interpreting the carryover of Professor Fairbanks' changes in his teaching practices for conceptual change into the different context.

Professor Fairbanks initially assessed the students' background in both classes and used this to determine his starting point. In the first class he began, "You guys had Modern [physics] with me so you did a little relativity…but you guys who are in Modern now have not done relativity yet" (PHYS 3000 Class Observation, October 2, 2013). And in the second class, "I think Mary you are going to be the only one who has completed Modern and everyone else is in Modern….We will start with one [experiment] which you are probably most familiar and that is blackbody radiation" (PHYS 3000 Class Observation, October 7, 2013). This background determined where Professor Fairbanks started the class. In the first class, he had taught the majority of the students Modern Physics and so he began with an experiment (Michelson's Interferometer) that tied in with relativity, a subject occurring at the end of Modern Physics. In the second class as most students were now just taking Modern Physics, he began with blackbody radiation, a subject students taking Modern Physics would have just covered.

After establishing the students' background, Professor Fairbanks sought to draw out the students' knowledge about the background of the experiment. In the first class, his initial focus was more about drawing out the historical context and significance of the experiment. His initial questions were, "So has anyone ever heard about Michelson? Who he was and why he is important? And interferometer?…When are we talking about with Michelson? What time period?" (PHYS 3000 Class Observation, October 2, 2013). In the second class, his questions were more focused on the concepts behind the experiment drawing out more students' ideas, which he guided to establish the key points of the background of the experiment.

> [Professor Fairbanks] So what do you know about it [blackbody radiation]?
>
> [Student] Basically any object that has heat will emit some form of radiation…
>
> [Professor Fairbanks] Okay. So what do you mean by, has heat?
>
> [Student] Well, more like has energy.
>
> [Professor Fairbanks] Is that the case? Okay.
>
> [Student] And the more energy you have the higher the energy you emitted.

[Professor Fairbanks] How do we measure that energy?

[Student] The energy emitted is equal to-

[Professor Fairbanks] No, the energy that it has what other word would we use for that?

[Student] Temperature.

[Professor Fairbanks] Temperature. Okay, so that is going to be a measure of the average energy per particle in some way. That is what temperature is. So the more temperature it has the more it does what?

[Student] It starts to emit higher frequency electromagnetic radiation.

[Professor Fairbanks] So the higher the temperature.

[Student] The shorter the wavelength is

[Professor Fairbanks] The frequency. The shorter the wavelength the higher the frequency and there is what else? So the wavelength changes when you heat up….What about the amount of radiation?

[Student] Intensity. More intesity

[Professor Fairbanks] More intensity....The total power radiated goes with the temperature to the 4th. So it is very non linear….Let's take a look at what we have back here. (PHYS 3000 Class Observation, October 7, 2013)

In this discussion, elements of the moderated class discussion utilized in teaching for conceptual change were present. Professor Fairbanks solicited students' ideas, refined the ideas, and guided them to key ideas. Then he demonstrated a blackbody experiment, which historically provided a discrepant event to the accepted theory.

In the first class, the students did not provide their own ideas from which Professor Fairbanks could establish the background for the experiment. Instead, he presented the historical account through direct instruction to set up the discrepant event of the Michelson Interferometer experiment and used this as the answer for, “Why we would bother to look at interferometer?” (PHYS 3000 Class Observation, October 2, 2013).

A predominant pattern of direct instruction occurred in both classes. The stated aim of the class to provide the background for five experiments lent itself to this. Professor Fairbanks acknowledged this during the classes and recognized he was losing the focus of the students. “And I left my notes in the office so hopefully I can actually reproduce this. I'm losing you all” (PHYS 3000 Class Observation, October 2, 2013). In the second class, he also acknowledged this, asking, “Are your brains getting a little tired now or are you doing okay? So this is the hardest one to explain....We've got a little more yet to go to explain what we are going to do here.” (PHYS 3000 Class Observation, October 7, 2013). Discussing this later, Professor Fairbanks pointed out, “So there was a lot of stuff I was trying to convey in that class…There was a lot of direct instruction going on there, but I'm trying to set the foundation for five experiments in one class period” (Interview, October 9, 2013).

Professor Fairbanks elaborated on the tension stemming from a ‘competing goal’ he had for the class. “I don't want to kind of just lay it all out for them like the cookbook stuff they're used to, but yet they needed some framework to get something out of it.” (Interview, October 9, 2013). He realized, “that if they didn't have a framework at all on some of these [labs] for what they were walking into, it wasn't going to be useful discovery” (Interview, October 9, 2013). A time pressure was identified, “I'm going to have five groups working next week when we start these [labs] and if they are all lost, it's going to be an hour before they're all going on something” (Interview, October 9, 2013). So these classes were designed to provide the background to help establish the framework. Professor Fairbanks stated,

> My goal in this was really to put them in a place where they have a basic understanding…of physics they were walking into…how it connected with the piece of equipment that was in front of them so that they could start doing – investigate some questions related to that. (Interview, October 9, 2013)

Professor Fairbanks illustrated the process with a painting metaphor. He explained,

> I am going to give you the landscape and you may have to go in and start investigating the trees and the bushes a little bit more on your own….The painting, right, may be that you have from [introductory physics] is kind of impressionist….You got to work on turning that into more photographic and the details make some sense. (PHYS 3000 Class Observation, October 2, 2013)

Major differences were noted between the two classes. The second class included changes in the order of instruction, drawing out students' knowledge more with questions, having students make more predictions prior to the demonstrations, and allowing students' questions to drive more aspects of the class. Professor Fairbanks acknowledged the second class connected more with the students' prior knowledge,

> So I see where they are the first time we did this, realizing that they were sort of quickly lost and the second time able to anticipate kind of where they were and, therefore, maybe present it in a more coherent way than built on what they already understand. (Interview, October 9, 2013)

He continued, "So I guess it connected a little bit more going from things I thought they would be firmer in to a little bit more things into the future that they will be seeing" (Interview, October 9, 2013). Professor Fairbanks exhibited a metacognitive process of reflecting on how the students learned in the first class and then readjusting the order and approach to better connect with them in the second class.

Throughout the upper-level lab classes, elements of conceptual change were identified. These were especially prevalent in Professor Fairbanks' goals for the class seeking to transform the students' approach to labs from a cookbook-like rule-following to an actively engaged scientist. Professor Fairbanks' framework for teaching for conceptual change was evident in his envisioning and planning the class. His own metacognition in evaluating the effectiveness of his teaching was noted. In his actual teaching practice, evidence of teaching for conceptual change was limited. Aspects of moderated class discussions of drawing out students' ideas were visible, especially the first step of soliciting students' ideas. As the class progressed, the instruction shifted to direct instruction and turned into primarily a lecture class leading up to a few demonstrations. Within the lecture, historical accounts of conceptual change were showcased around the demonstrations. Several constraints were identified. The essential one was a time pressure to make sure the students had some background knowledge prior to beginning the experiments. Overall, Professor Fairbanks exhibited a framework of conceptual change in conceptualizing the class. Yet, in his execution, he was challenged to successfully implement teaching for conceptual change in a different context as observed in this limited setting.

Summary of physics professor's practices of teaching for conceptual change.

Over the two years of study, Professor Fairbanks' practices of teaching for conceptual change evolved into more defined and integrated methods of instruction (Appendix K). Key to this was the collaboration with the science education professor. Through Professor Fairbanks' observations and interactions with the science education professor's instruction and modeling of teaching for conceptual change, a pattern of emulation and assimilation was noted. An important catalyst in the Professor Fairbanks' changing practice was the independent instruction required of him, due to the science education professor's absence during the second summer. A greater integration of Professor Fairbanks' theoretical framework for conceptual change with his instruction resulted as he adapted his pedagogy to instruct and model conceptual change. The most pronounced changes in Professor Fairbanks' practices followed the resuming of the collaboration at the end of the second summer. Teaching alongside an expert, Professor Fairbanks' practices advanced, characterized on the continuum of conceptual change categories as progressing into the Conceptual Change Novice View category. Throughout the two years, limitations in Professor Fairbanks' practices associated with time, competing interests, and limited confidence persisted. The carryover of Professor Fairbanks' practices for teaching conceptual change to a different context (upper-level lab course) showed the framework being used in planning and evaluation, but restricted in the actual instruction. In the next section a closer look at the factors which facilitated or hindered changes in Professor Fairbanks' conceptions and practices is presented.

Learning Environments Effect on Teaching for Conceptual Change

Characteristics of the learning environment, which either facilitated or hindered change in Professor Fairbanks' conceptions and practices of teaching for conceptual change, are examined in this section. As discussed in the literature review, learning environments include the social, psychological, and pedagogical contexts where learning occurs and take place at multiple levels from the classroom environment, to the school environment, to out-of-school environment (Fraser, 1998). Likewise, the same structure, starting at the classroom level followed by the departmental level, the professional community level, and the university level, was used to examine the learning environment factors, identified by Professor Fairbanks within the findings that helped facilitate or hinder changes in his conceptions and practices. Those factors which helped facilitate changes in Professor Fairbanks are examined first followed by those which hindered or limited his changes.

Learning Environments' Facilitators of Change

Classroom level.

Improve student learning.

Professor Fairbanks' desire for improved student learning was a key motivator in his desire to change his teaching practices. His exposure to PER methods of teaching at the new faculty workshop and the discovery of the limited effectiveness of his own teaching methods fostered a dissatisfaction with the traditional methods of teaching and a willingness to try alternative approaches. He stated in reflecting on why he continued to try to implement PER-based teaching methods as a *lone wolf*, "It was a moral question. It's just not possible to go back and…teach the way I like the best, if that's not most effective" (Interview, June 10, 2013). This belief in his duty to provide the best instruction to facilitate student learning was a key factor in his early adaptation of PER and openness to learn more about conceptual change. This factor was also evident in his transitioning into educational research. As he distinguished in contrasting educational research with his physics research, he explained, "What we're learning can have a lot of positive impact… it's the interaction with the students… and how can we … help them" (Interview, June 10, 2013).

Collaboration with an expert.

The collaboration with the science education professor in PHYS 7050 was a central factor in the observed changes in Professor Fairbanks' conceptions and practices. As discussed, the collaboration was divided into two phases: initial collaboration and resumed collaboration.

In the initial collaboration, the science education professor presented a more comprehensive overview of conceptual change theory drawing from key articles. This instructional content of the science education professor influenced the conceptions and practices of Professor Fairbanks. As he reflected in an early class, “[Professor Crefeld] discussed Hesse article and had really good discussion on bringing about conceptual change….This matched up really well with discussion of lab activities and why you do labs…dove-tailed nicely here” (Professor Fairbanks’ Journal Entry, June 14, 2012). Professor Fairbanks drew from this theory and connected his own instruction to it. He began to adopt the language of conceptual change which Professor Crefeld was utilizing. Representative of this embracing of conceptual change vocabulary was Professor Fairbanks concluding statement on discussing teaching Newton’s Laws of Motion. He concluded, “The students have to see it as plausible” (Class 10 Observation, July 5, 2012).

Professor Crefeld’s modeling of strategies for teaching conceptual change in his instruction also influenced Professor Fairbanks’ practices. This was evidenced in his emphasis on students’ predictions in labs, engaging the students in “meta-thinking” discussions concerning their possible initial conceptions, and his attempt at more open-ended discussions. On a class discussion centered on the PHYS 7050 predicting issues students would have representing forces and their teaching responses to them, he summarized, “This took a lot of time but it was totally worth it since there were a number of misconceptions that came out and … made… inconsistencies more apparent to the students” (Professor Fairbanks’ Journal Entry, July 5, 2012).

The period of independent instruction before the resumed collaboration was a key catalyst for Professor Fairbanks’ change. During this time, Professor Fairbanks was forced, on his own to teach and model teaching for conceptual change. This required him to evaluate his instruction from a conceptual change point of view and attempt to model teaching for conceptual change, despite his natural hesitation. When the resumed collaboration began, Professor Crefeld, provided more explicit and focused instruction on teaching for conceptual change. This detailed instruction and modeling targeted many of the areas Professor Fairbanks was struggling to enact. As Professor Fairbanks stated, “He [Professor Crefeld] talked a little bit more explicitly… how it works when he was trying to lead those kinds of discussions…. I needed that lesson earlier… I was struggling with being able to lead those kinds of discussions” (Interview, July 31, 2013).

In response to this targeted instruction and modeling, Professor Fairbanks first emulated and then integrated many of these into his own instruction. His effectiveness in modeling student-centered instruction through moderated class discussions as demonstrated above in several excerpted class discussions (e.g., momentum and buoyancy) revealed the extent of these changes. Both the nature of the collaboration and the progression of the collaboration (initial collaboration followed by independent practice followed by a resumed collaboration) were key learning environment characteristics in facilitating change in the physics professor.

Collegiality.

The personal relationship between the science education professor and the physics professor within PHYS 7050 fostered an environment of mutual respect and collegiality. A mutual respect was shown in both professors acknowledging the expertise of each other. For example in Class 9, Professor Crefeld led the class through a demonstration on the concept of thermal conductivity. He used it to illustrate the use of making models, deferring the instruction on the concept of heat to the expertise of Professor Fairbanks. Professor Crefeld remarked,

> The purpose of this is not to teach you about the concept behind this: heat, thermal conductivity, temperature…Professor Fairbanks [turns and acknowledges Professor

Fairbanks, Professor Fairbanks smiles back] is teaching you about that the last week of class. So I hope you'll have a nice anchoring event to refer back to. (Class 9 Observation, July 16, 2013)

This environment of collegiality supported the personal interactions of the two professors, exchanging ideas and linking their instruction to each other as highlighted in the resumed collaboration findings. It allowed Professor Fairbanks to attempt ideas with the science education professor prior to sharing them with the class. A powerful example was Professor Fairbanks' evolving understanding of changing students' frameworks utilizing FCI responses in the last two classes. A key element was his private discussion with Professor Crefeld which helped solidify his ideas that he then articulated to the class. He explained the process, "You present the expert conception on the concept. So now we are trying to close that loop by working through and looking through answers and understanding; what is the framework we are actually trying to work towards" (Class 13 Observation, July 25, 2013). An environment where Professor Fairbanks felt comfortable to share his emerging ideas was vital for developing more sophisticated ideas and practices of teaching for conceptual change. This collegiality created a safe environment which helped support the risk involved in change.

Department level.

Position of influence.

Professor Fairbanks' position in the physics department as undergraduate director and as a senior-tenured professor was key in the development of PHYS 7050 and his involvement in the subsequent collaborative co-teaching of it. Professor Fairbanks used his position as undergraduate director to drive departmental-wide changes to further support student learning. As detailed in his background discussion, Professor Fairbanks' dissatisfaction with the limitations of what the physics department offered MAT students and prospective physics teachers motivated him to seek expertise outside the physics department. This led to collaborations with the College of Education. As he stated, "Involve the College of Education as much and in every way that we can because, it's going to be for the benefit of the students" (Interview, June 5, 2012). Professor Fairbanks' concern about the instruction in the upper-level lab course motivated him to resume instructing it after having stepped away for a couple of years. He explained,

> So he [previous instructor] recognized that there was a problem…that they [students] didn't know how to use these things [lab equipment], he didn't have a response to it. Basically, I didn't understand that, so that's one of the reasons why I felt like I had to take this [PHYS 3000] back over….The reason we created this course is to be explicit about preparing them to be able to do experiments and … a research project. (Interview, October 9, 2013)

His senior position allowed him to resume teaching the course. Being a senior, tenured professor permitted Professor Fairbanks more autonomy to pursue these collaborations and changes. As he stated, "I don't really know what people outside the department…and the rest of the department really thought, I wasn't really looking for their approval on things. To some extent, having tenure, I didn't have to have everybody liking me" (Interview, June 10, 2013).

Environment of active reform.

The physics department's initiatives, targeting student learning and educational research, were important elements, setting the groundwork for the development of PHYS 7050 and initiating many of the subsequent changes within Professor Fairbanks. As identified earlier, the hiring of a PER faculty member in the department allowed Professor Fairbanks to become involved in joint educational research. As a practicing educational researcher, he was further exposed and prepared for the adaptation and utilization of conceptual change theory. The establishment of the reform-model (SCALEUP) studio classroom for introductory physics provided the context for the student teaching practical component of PHYS 7050. These established reform initiatives created a more open environment to promote educational reforms, many of which were initiated by Professor Fairbanks. No longer was he "a lone wolf" reformer as he related, "Within the department, we've got one other physics education research faculty member… and we've got three lecturers in physics…all very interested in physics education research, the best practices, and also being involved in research" (Interview, June 10, 2013).

Time for reflection on practice and research.

A common theme of time for reflection on practice and research emerged in discussions with Professor Fairbanks concerning change in his conceptions of teaching and learning. These times of reflection were associated both with educational research that he was involved in and being a participant in this study. These generated a metacognitive thinking leading to a deeper understanding and changes in his teaching and learning practices. The examples Professor Fairbanks provided were the reflections forced by the interviews carried out in this study. He acknowledged, "You're asking me questions as well in the interviews about this and that…and so that also forces me [to reflect]" (Interview, July 31, 2013). Questions, emerging from his reflection on FCI results between the two years of PHYS 7050 as well as from his research on different types of classes, were cited as additional examples. He stated, "The FCI is … a way we can compare with other institutions. So it leads us to be able to ask a lot of questions then we could otherwise" (Interview, July 10, 2013).

Professional community level.

PER community exposure and involvement.

Professor Fairbanks' exposure and familiarity to PER, prior to the collaboration, provided a base of prior knowledge that complemented the concepts of teaching for conceptual change, making it intelligible. Professor Fairbanks identified the core of PER as "trying to develop an understanding of how students learn, particularly how they learn physics" (Interview, June 10, 2013). Professor Fairbanks was already focused on students' learning, valuing students' ideas, and targeting common physics misconceptions prior to the collaboration. Yet, in Professor Fairbanks' view, his use of PER was as a diagnostic tool, "looking at that what works and what doesn't work" but not providing a unifying framework on "how students are thinking and how students learn" (Interview, July 23, 2012). Professor Fairbanks' awareness of his limitations in utilizing PER and desiring a more unifying framework for understanding students' learning provided a fertile ground for conceptual change theory with its explanation of how students' learn.

University level.

Institutional change initiatives.

A key external learning environment factor was an institutional culture of change. As identified in the background, the PHYS 7050 collaboration was a direct result of national reforms and policies to overhaul science teacher preparation programs. At the university level, the PRISM initiative (Jones, 2008) provided a mini-grant which allowed for the time release for both professors to develop and co-teach PHYS 7050. As Professor Fairbanks recalled, "The development of the class [PHYS 7050] for MAT students. That was funded by the mini-grant program" (Interview, June 10, 2013). Other initiatives within the university, such as STEM community and collaborations with PhysTEC (2013), showed these changes which played a key role in Professor Fairbanks' development. He remembered, "I was part of a couple of PRISM mini-grants…and then … STEM Initiative, and there was a mini-grant program for doing that. So I've been part of a few different projects" (Interview, June 10, 2013). The culture of change within the university was noted by Professor Fairbanks, who remarked,

> Interaction with the people in the College of Ed… in the past there wasn't much connection, so now there's more things we have crossing the lines…more interactions and collaborative efforts between Arts and Sciences and College of Ed. Times have changed a lot. A huge amount from fifteen years ago. (Interview, June 10, 2013)

Learning Environments' Hindrances to Change

Classroom level.

Expediency of traditional instruction.

A pattern highlighted throughout Professor Fairbanks' instruction was reverting back to direct instruction when time pressure was felt. About his momentum instruction during the first summer, he stated, "With limited time I opted for some direct instruction to try and give the big picture" (Professor Fairbanks' Journal Entry, July 5, 2012). While he advocated alternative types of teaching, a pattern of direct instruction persisted in his teaching. Reasons identified for this practice included a desire to cover the material to help improve content knowledge of the students and prepare them to teach the material in the Studio classroom. As he reflected, "I feel a lot of tension between teaching content, modeling the kind of teaching we want them [students] to do, and giving them practice at leading the activity….I end up doing a speed teaching with too much lecture" (Professor Fairbanks' Journal Entry, June 26, 2012).

An incongruence between his expressed conceptions of teaching and his classroom practice persisted, limiting his ability to consistently model teaching for conceptual change.

Limited confidence.

Professor Fairbanks exhibited limited confidence in implementing newer approaches for teaching for conceptual change. When stressful circumstances, such as time pressure occurred, he would revert back to more traditional methods. Additionally, he would defer to the science education professor whenever possible concerning teaching for conceptual change, as detailed in his independent teaching period. This was captured in his admission about leading conceptual change discussions where he stated, “Although I’ve learned a lot, I don’t feel comfortable enough to be able to actually lead those kinds of [theoretical conceptual change] discussions” (Interview, June 12, 2013).

The majority of the change exhibited in Professor Fairbanks’ practice occurred when the science education professor was present, providing a safer environment. Professor Fairbanks’ limited confidence was a hindrance to the extent he exhibited independent change.

Absence of an expert in teaching for conceptual change.

The nature of the collaboration between the physics and science education professors in PHYS 7050 primarily occurred during class time. In addition, this was further limited during the second summer to four classes due to the science education professor’s schedule. As discussed previously, most changes in regards to Professor Fairbanks’ conceptions and beliefs occurred in the context of the collaboration. Change apart from the modeling and tutelage of an expert was limited. A key example was Professor Fairbanks’ change in his ability to lead moderated discussions to model teaching for conceptual change. In the period of his independent practice, Professor Fairbanks attempted on his own to lead these discussions as he had seen Professor

Crefeld use so effectively. While progress was seen, the majority of the discussions were dominated by Professor Fairbanks' instruction with the students' responses being brief interludes. This contrasted sharply with the student-centeredness of Professor Fairbanks' moderated discussions on momentum and buoyancy during the resumed collaboration with the modeling and tutelage of Professor Crefeld.

With the context of collaborating with an expert restricted primarily to class time, the potential reach of this change outside of the immediate setting of the PHYS 7050 classroom was narrowed. Evidence was seen in the limited transfer of teaching for conceptual change by Professor Fairbanks in the upper-level lab course. So the absence of an expert to help model and understand concepts in different contexts was a major limitation to change.

Department level.

Departmental indifference.

As profiled, Professor Fairbanks was highly motivated to improve student learning both in his own teaching and within his department. As discussed in his background, within his department many of his early efforts were met with indifference. As he recalled following his first exposure to PER, "I gave a department colloquium about stuff [PER] I'd heard about….Nobody was interested at all in that, at that point" (Interview, June 10, 2013). Much of the change he accomplished within the department occurred only after he had assumed a leadership role with the power to initiate change. These changes were subject to being undermined by others in the department, as illustrated in the upper-level laboratory class. As Professor Fairbanks relayed,

> I got info from the previous instructor, he said, "I've done a lot of meters, most of them have their fuses blown… so I just stopped putting fuses in them… So he recognized that

> there was a problem…that they didn't know how to use these things, he didn't have a response to it." (Interview, October 9, 2013).

Here the previous instructor identified there was a problem, but only addressed a symptom of the problem – blown fuses, instead of the deeper root of the students not understanding how to measure electricity. More troubling was his satisfaction with having addressed the problem of broken meters and his imperviousness or at least indifference to needing to address the lack of understanding in the students. This was one example of a departmental indifference Professor Fairbanks struggled against. This departmental indifference provided a strong inertia against change.

Professional community level.

Participating in educational research.

Becoming an educational researcher was a long, involved process for Professor Fairbanks as he had to overcome a lot of barriers. It was a completely different way of looking at teaching and conducting research than the traditional methods of the physics community. As Professor Fairbanks recounted, "A lot of barriers to learning the field, but also learning the techniques. It's a totally different way to go about research" (Interview, October 9, 2013). Having others understand and appreciate his work in educational research as distinctive from his instruction was a major challenge. He explained,

> There's the distinctions between what you're doing and what's instruction and what's research….There are a lot of barriers to making that transition [into educational research]. And because the lines are blurrier for a lot of people on the outside, including past department chairs…who didn't understand these distinctions. (Interview, October 9, 2013)

Overcoming these barriers required the help and tutelage of an expert. For example Professor Fairbanks' learning of PER began through a new faculty workshop led by experts in the field. Professor Fairbanks' increased involvement into educational research began after the hiring of a PER faculty member by the physics department. He recalled, "So it was really the hiring of Dr. Nora that changed things, because now…there was an opportunity to be a part of that [educational research] without having to go and figure out how to do it all by myself" (Interview, June 10, 2013). These barriers were evident in the classroom as well as in Professor Fairbanks' reluctance to teach the theory of conceptual change and his deferring of those discussions until an expert [Professor Crefeld] was present. So the barriers of entering and participating in another field and professional community accomplished through the help of an expert became a limitation to the change process.

University level.

Policies and traditions.

Collaborations between colleges as demonstrated in PHYS 7050 were very rare. Most of the collaborative efforts Professor Fairbanks mentioned were forged by highly motivated individuals working to overcome institutional hurdles. Issues, like time release and funding often limited the possibility of collaborations, requiring additional funding through grants and other outside initiatives. Traditional university culture promotes research over instruction. Professor Fairbanks, reflecting on the policies for tenure, stated,

> The Promotion and Tenure Manual is written in such a way that if you did well on your research, you automatically did well in your instruction rating. For instance if you bring in external money, you score graduate students that's one of the check marks that gets you a higher rating in instruction.…you could focus on your research and get all these tic

marks and not really have to pay attention to your classroom teaching. (Interview, October 9, 2013)

These policies and traditions provided serious challenges to overcome in initiating change, spanning the divide between different institutions.

Summary of the Findings

Within this section, a profile of the physics professor was characterized by his background and motivation leading to the collaboration. Five emergent conceptual categories for teaching for conceptual change were identified and detailed (Table 3). These categories were then used as a continuum upon which Professor Fairbanks' expressed conceptions and practices for teaching for conceptual change were projected. Professor Fairbanks' conceptions and practices, respectively, were evaluated at specific periods of the study: preliminary to the collaboration, the initial collaboration, the planning stage, independent practice, the resumed collaboration, and an extended practice. This analysis, based on the physics professor's expressed words and acts, presented the evidence of change in both his conceptions and practices for teaching for conceptual change. Finally, factors, which either facilitated or hindered this change, were identified. These findings are discussed in the next section, grounding them in the literature reviewed and providing conclusions and recommendations from the study.

Table 3

Emergent Categories of Approaches to Teaching for Conceptual Change

Categories	Approach	Object	Characteristics
Transactional	Teacher-centered	Content-oriented	Direct instruction Teacher as expert Students learn by being told Lack of effectiveness in student's learning
Active Teaching	Teacher-centered	Content-oriented	Expert pedagogy Identifying students' preconceptions Concrete teaching methods Active participation of students Lacks underlying framework and limited applicability
Students' Ideas	Teacher-centered	Learning-oriented	Students expressing preconceptions Matching emerged conceptions with developed pedagogy strategies Create conflict between students' conception and science conceptions to emphasize difference Lacks underlying framework. Focuses on data comparisons over framework construction
Students' Learning	Student-centered	Learning-oriented	Focus on how students learn Facilitating students' expressing their ideas Engaging students with their ideas for consistency and context Limited metacognition and framework construction
Conceptual Change	Student-centered	Framework-oriented	Focus on students' framework
Novice View			Focus on connecting ideas into a framework Developing metacognition Abstract view of framework Limited integration of framework
Expert View			Focus on changing framework Concrete view of framework Integrated framework used to evaluate pedagogy Developed metacognition in students Instruction focus on making explicit tacit understanding Individual adapts framework to the other contexts

5 DISCUSSION

The purpose of my study was to (a) understand the change process of a university professor in response to a teaching collaboration with an expert; (b) identify the resulting changes in the professor's conceptions and practice; and (c) understand the facilitators and barriers to the change process identified by the professor. One research question and three sub-questions guided the study through the data collection, data analysis, and presentation of the research findings. The overarching research question was: How is teaching for conceptual change conceptualized and practiced by a physics professor during and beyond an extended collaboration with a science education professor focused on teaching for conceptual change. The sub-questions were:

1. What is the evidence of change in a physics professor's conceptions of teaching for conceptual change?
2. What is the evidence of change in a physics professor's practices of teaching for conceptual change?
3. What are the learning-environment characteristics identified by the physics professor that either facilitated or hindered changes in his conceptions and/or practices in teaching for conceptual change?

This chapter consists of (a) a summary of the research findings in relation to the sub-questions, followed by a section responding to the overarching question; (b) a discussion of the findings in regard to existing literature; (c) a conclusion explaining how the study adds to the literature regarding the change process on a university professor's conceptions and practices for teaching for conceptual change resulting from a collaboration with an expert (d) a section of implications for those studying or seeking change in university professor's conceptions and practices through collaborations with experts; and (e) a section for recommendations for future study.

Overview of the Findings

My research study involved a phenomenographic case study conducted with a senior, physics professor. It followed the physics professor's extended collaboration with a science education professor focused on teaching for conceptual change. An introductory physics course (PHYS 7050) for pre-service science teachers was the main context of this study. The primary data were interviews with the physics professor combined with direct classroom observations. The focus in the analysis was the physics professor's words and acts centered around teaching for conceptual change (Entwistle, 1997; Marton & Booth, 1997). The data analysis involved an iterative process of deconstructing the transcribed interviews and observation recordings and then compiling related pieces into categories of descriptions, representing the different ways of understanding teaching for conceptual change identified by the physics professor (Akerlind, 2012; Dahlgren, 1997; Hasselgren & Beach, 1997). Key structural relationships of these categories were delineated through a continual comparison and contrasting (Akerlind, 2012).

Five distinctive categories of teaching for conceptual change emerged: a) transactional teaching approach; b) active teaching approach; c) students' ideas approach; d) students' learning approach; and e) conceptual change approach divided into a novice view and an expert view. The first two categories reflected predominately teacher-centered traditional teaching. The three upper categories, as illustrated in Figure 9, showed a progression in the sophistication of teaching for conceptual change, transitioning from focusing on individual students' ideas to students' frameworks constructed of connected ideas.

The emergent categories were used to identify the change in the physics professor's conceptions and practices of teaching for conceptual change. To situate the change, six distinctive periods of the study were identified and analyzed.

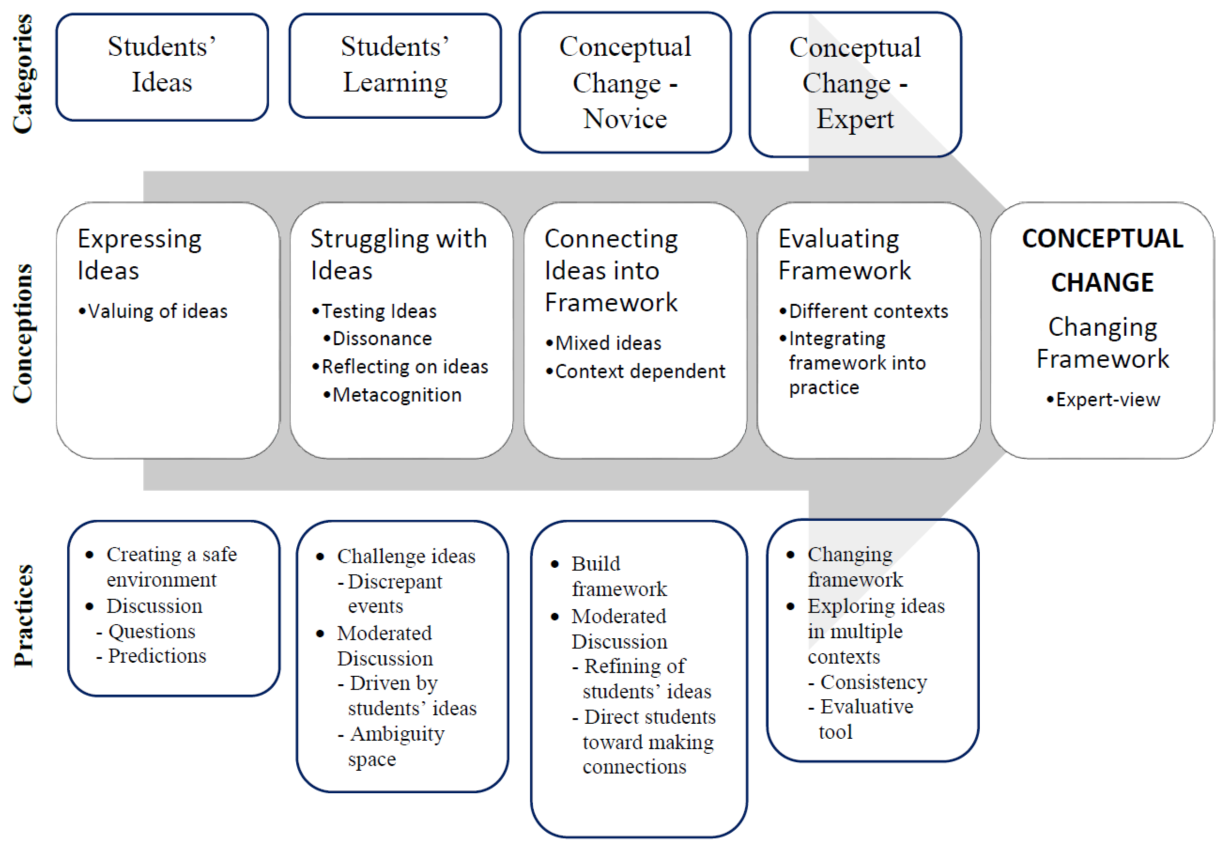


Figure 9. Emergent Categories of Teaching for Conceptual Change. The identified conceptions and practices of the higher three emergent categories are shown along with their hierarchical structure superimposed on a teaching for conceptual change framework.

These periods of study were: preliminary, initial collaboration, planning, independent practice, resumed collaboration, and extended practice (Appendix K). On this framework the first two research sub-questions of the study were analyzed. The sub-questions considered were:

(1) What is the evidence of change in a physics professor's conceptions of teaching for conceptual change?

(2) What is the evidence of change in a physics professor's practices of teaching for conceptual change?

The physics professor's words and acts describing and demonstrating his conceptions and practices during each period were analyzed. Characteristic examples were presented for each period to demonstrate his current state as well as changes within his conceptions for teaching for conceptual change, followed by his practices for teaching for conceptual change. A summary of these findings is displayed in Table 4.

The change in the physics professor's conceptions and practices was identified by situating it within the emergent categories for each period and comparing them (discussed in more detail later). A general progression toward a more sophisticated view in both conceptions and practices was noted except during the extended practice which revealed mixed results. The physics professor's conceptions led his practices in their sophistication. The largest change in both conceptions and practices occurred between the physics professor's independent practice and the resumed collaboration.

The facilitators and hindrances to change within the physics professor's conceptions and practices for teaching for conceptual change were identified (Table 5). These findings provided the evidence for the third research sub-question, What are the learning-environment characteristics identified by the physics professor that either facilitated or hindered changes in his conceptions and/or practices in teaching for conceptual change? These changers were situated in the learning environments of the classroom, departmental, professional community, and university levels (Fraser, 1998).

Table 4

Summary of Evidence for Changes in the Physics Professor's Conceptions and Practices of Teaching for Conceptual Change

Period	Type of Change	Evidence
Preliminary	Conceptions	• Valuing students' ideas – ideas not wrong, limiting • Teaching directly responsive to where the students are • Creating conflict between students' ideas and how things work • Need for students to develop alternative theory
	Practice	• Establishing a safe environment for students' ideas • Using discussion to help students' ideas emerge • Connecting provided theory with the practice of learning physics • Tension between instruction and modeling
Initial Collaboration	Conceptions	• Valuing how students' ideas form • Teaching focused on underlying framework (why behind students' thinking) • Focus on students talking about ideas (what and why) • Make students aware of their thinking (metacognition)
	Practice	• Influence of science education professor's instruction (vocabulary) • Using discussion to solicit students' ideas on possible preconceptions • Time for students to compare their ideas with the new idea (plausibility) • Recognized and articulated tension between instruction and modeling
Planning	Conceptions	• Value of students struggling with their ideas • Teaching engaging in open discussion (students struggle with their ideas) • More developed theoretical framework for conceptual change • Evaluating pedagogy through lens of framework
	Practice	• Greater articulation of conceptual change process • Discussion emphasis on students' engaging their ideas • Difference between conceptions and practice (tension) • Limited confidence in teaching framework of conceptual change
Independent Practice	Conceptions	• Valuing of developing student framework • Teaching focused on students establishing framework through discussion on activities • Integrating of framework into pedagogy • Shifting from inward focus (being expert) to outward focus (students developing their ideas)
	Practice	• Elicit key elements of conceptual change through discussion and questioning • Using concrete examples to demonstrate teaching for conceptual change • Improved ability to facilitate class discussions and use of explicit vocabulary • Tension between modeling and preparing students
Resumed Collaboration	Conceptions	• Valuing of changing students' framework • Teaching focused on framework development • Importance of metacognition (students and teacher) • Evolving concept of context-dependent ideas forming stable frameworks
	Practice	• Emulation and assimilation of science educator's instruction • Assimilation of class discussions as effective tool for modeling teaching conceptual change • Limited metacognition and consistent integration
Extended Practice	Conceptions	• Changing students' approach to labs • Evaluating understanding of models • Ideas of filling knowledge gaps
	Practice	• Conceptual change limited to envisioning the class and evaluating teaching • Instruction in class focused on informing students

Table 5

Identified Facilitators and Hindrances to Change in the Physics Professor's Conceptions and Practices of Teaching for Conceptual Change

	Learning Environment Levels			
	Classroom	Departmental	Professional Community	University
Facilitators	Desire to improve student learning (self-efficacy) Collaboration with expert • Nature of collaboration - Learning content - Modeling practice • Progression of collaboration - Initial collaboration→ independent practice→ resumed collaboration Collegiality	Position of influence • Leadership role • Tenured Environment of active reform Time for reflection on practice and research	PER community exposure and involvement	Institutional change initiatives
Hindrances	Expediency of traditional instruction • Time pressure • Preparation of students Limited confidence Absence of an expert in teaching for conceptual change • Difficulty modeling • Limited transfer to other contexts	Departmental indifference • Resistance to change	Participating in educational research • Learning the field • Participating in the field	Policies and traditions • Research centered • Institutional hurdles to collaboration

Discussion of Results

A discussion of the results situating them in the existing literature (Chapter 2) is the focus of this section. This discussion goal provides a perspective on how this study added to the understanding of the change processes within university faculty members resulting from collaborations with experts. Similarities and differences between the reviewed literature and the research findings are argued. The discussion follows the order of the presented findings beginning with the emergent categories, the evidence related to the three research sub-questions, and concludes with evaluating findings in relation to the overarching question.

Emergent Categories

Similarities with other phenomenographic studies.

Traditionally research studies on university professors' conceptions on teaching and learning revealed the conceptions classified within the broad categories of teacher-centered/content oriented and student-centered/learning oriented (Biggs & Tang, 2011; Kember & Kwan, 2002; Pratt, 1992; Prosser et al., 1994; Vermunt & Verloop, 1999). Comparing my emergent categories of teaching with five phenomenographic studies on teachers' conceptions of teaching (Table 6) revealed similar hierarchical structures from a teacher-centered view in the lowest categories, transitioning to a student-centered view in the highest categories with progressive categories inclusive of the ideas of the lower categories (Akerlind, 2004; Dall'Alba, 1991; Martin & Balla, 1991; McKenzie, 2003; Prosser et al., 1994). The range of emergent categories fell within the extent of the other studies. The lowest category of a transactional view of teaching lined up closely with all the other studies' emphasis on teacher's transmitting information. The highest emergent category of conceptual change – expert view with its emphasis on changing students' frameworks aligned with both Dall'Alba (1991) and Prosser et al.'s (1994) most sophisticated categories of bringing about conceptual change and helping students change conceptions, respectively. All the intermediate emergent categories were reflected in categories of other studies. This aligning of the emergent categories with previous studies suggested that the variation of the physics professor's conceptions of teaching covered the mapped range of conceptions of teaching.

Differences with other phenomenographic studies.

Several differences between this study's emergent categories and the previous phenomographical studies included this study's focus on teaching for conceptual change and the inclusion of both conceptions and practices within the categories. While both the Dall'Alba (1991) and Prosser et al.'s (1994) studies list conceptual change as their most sophisticated category, no other study focused specifically on the conceptions of teaching for conceptual change but instead focused more broadly on general teaching. The specific focusing on the more complex form of teaching for conceptual change helped explain the generally more sophisticated upper levels of the emergent categories (Figure 9).

Many researchers point to a connection between teaching patterns (practices) and a teacher's thinking of teaching (conceptions) (Kember & Kwan, 2002; Ramsden et al., 2007; Trigwell et al., 1999; Vermunt & Verloop, 1999). Most of these phenomenographic studies (Table 6) limited their categories of teaching only to teachers' conceptions based on interviews (Kane et al., 2002). The exceptions were Prosser et al. (1994), who identified seven categories of teachers' approaches to teaching and later concluded that a close relationship existed between them, and McKenzie (2003) who included both a structural aspect dealing with a teacher's view of teaching and a referential aspect focused on the method of teaching within her categories.

Table 6:

Comparison of Emergent Categories with Prior Phenomenographic Research Studies on Professors' Conceptions of Teaching

Sophistication Level	Stoll, 2015	Dall'Alba, 1991	Martin and Balla, 1991	Prosser, Trigwell and Taylor, 1994	McKenzie, 2003	Akerlind, 2004
Complex conceptions	Conceptual Change: Expert View	G. Bringing about conceptual change	3. Relating teaching to learning	F. Helping students change conceptions	F. Teaching as challenging and enabling students to change the relation between themselves and the world	
Student-centered	Conceptual Change: Novice View	F. Exploring ways of understanding from particular perspectives	2. Encouraging active learning: experiential focus vocational variation	E. Helping students develop conceptions	E. Teaching as guiding students to explore and develop professionally and become independent as learners	Student learning focused
	Students' Learning	E. Developing the capacity to be expert			D. Teaching as facilitative process of relating teaching to learning to help students to develop their own disciplinary or professional understanding	Student engagement focused
Intermediate conceptions	Students' Ideas	D. Developing concepts and their interrelations	2. Encouraging active learning: discussion focus	Helping students acquire: D. teacher's knowledge C. concepts of the syllabus		
Teacher-centered	Active teaching	C. Illustrating the application of theory to practice	2. Encouraging active learning: motivational focus		C. Teaching as teacher-focused interaction with students and student activity to help students to become capable of using the concepts and methods of the discipline or profession	Teacher-student relations focused
		B. Transmitting information	1. Presenting information: content organization focus	B. Transmitting teachers' knowledge	B. Teaching as organizing explaining, and demonstrating information so that students acquire disciplinary concepts and methods	
Limited conceptions	Transactional	A. Imparting information	1. Presenting information: delivery focus	A. Transmitting concepts of the syllabus	A. Teaching as transmitting information so that it is passed on to students	Teacher transmission focused

My study included both interviews and extended classroom observations of the physics professor, providing insights into both conceptions and practices in the classroom. Methodologically, audio transcripts of the physics professor's instruction capturing his words and perspective consistent with phenomenographic methods, were utilized for the inclusion of the physics professor's practices. This allowed for a more detailed analysis of both the conceptions and practices and how they were categorically linked. The emergent categories revealed a richer description of teaching, detailing both the focus of the teacher's thinking and practice.

Framework for teaching conceptual change.

Examining the framework of the emergent categories (Figure 9) in light of the referenced expert framework for teaching conceptual change (Hewson et al., 1998) revealed a hierarchical progression toward conceptual change. This represented the process of students' changing their frameworks into more expert-like frameworks. The lowest category of Students' Ideas included precursors of the first aspect of explicitly considering students' ideas in the classroom from the teaching for conceptual change framework. Students' ideas were becoming part of the classroom discussion, but were not yet treated with equal standing as teachers' ideas. In Students' Learning category, the first aspect was more developed with students' ideas driving class discussion. The second aspect of metacognition was emerging and the third aspect of the status of students' ideas being discussed and negotiated gaining emphasis. The negotiating status process at this time was not fully developed with an overemphasis on challenging ideas through discrepant events (lowering status) and less emphasis on raising status of ideas. In the Conceptual Change Novice View category, all four aspects of the framework were visible. In the developing of status, negotiated through open classroom discussions directed at helping students build frameworks, the justification behind status decisions was considered. While all four aspects were present, their explicit treatment in the classroom was limited and inconsistent. In the instruction, all of the aspects were taught, but in the practice not all were fully realized. In the final Conceptual Change Expert View all four aspects of teaching for conceptual change were emphasized. Evaluating frameworks in different contexts and using them as evaluative tools for ideas encapsulated the aspects of metacognition, status negotiating, and underlying justification criteria for idea adoption. Thus, this emergent model of conceptual change from the physics professor's conceptions and practices of teaching for conceptual change exhibited a consistency with the expert-view of teaching for conceptual change (Beeth & Hewson, 1999; Hewson et al., 1998).

Change in Conceptions and Practices

The physics professor exhibited changes toward more expert-like conceptions and practices of teaching for conceptual change through his collaboration with the science education professor. Change in conceptions preceded changes in practices (McKenzie, 2003; Trigwell & Prosser, 1996). As discussed in Chapter 2, traditionally teacher change was linked with PD which resulted in change in teachers' beliefs, practices, and their students' learning (Desimone, 2009; Guskey, 2002).

Framework of teacher change.

Clarke and Hollingsworth's (2002) IMTPG model reflected these key elements of change as four domains. The External Domain (ED) contained the PD. Teachers' conceptions comprised part of the personal domain (PeD) along with the teachers' knowledge and attitude. The domain of practice (DP) encompassed the teachers' practice. Lastly, the domain of consequence (DC) involved the students' learning. Change translating from one domain to another occurred through the mediating processes of reflection and enactment (Figure 10).

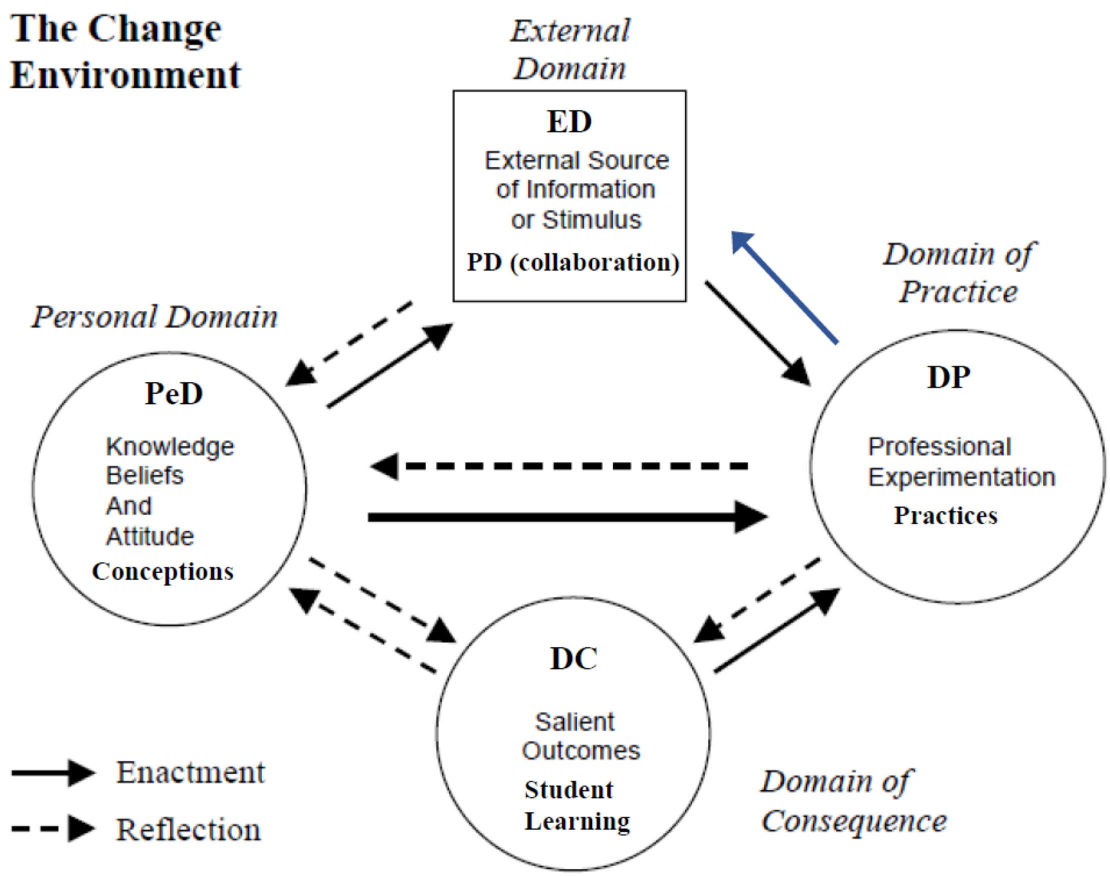


Figure 10. Modification of the Interconnected Model of Teacher Professional Growth showing a proposed enactment process from the domain of practice to the external domain. Adapted from "Elaborating a Model of Teacher Professional Growth," by D. Clarke and H. Hollingsworth, 2002, *Teaching and Teacher Education, 18,* p. 951. Copyright 2002 Elsevier Science Ltd.

Change in conceptions.

In the IMTPG model, three general processes led to change in the physics professor's conceptions (PeD): Reflection on the external domain (ED▪▶PeD) captured the changes of the physics professor's increased understanding of a framework of conceptual change influenced by the science education professor's instruction and modeling on teaching for conceptual change. A powerful example of this was Professor Fairbanks' response to the Gopnik video. He articulated the difference between a child's flexibility in testing ideas without a framework with scientists testing ideas within their framework. Scientists test by changing an idea and understanding the implications of that change on other interconnected ideas. The professor's participation in this study was another example. As he pointed out, " I had to reflect a lot more…and then you're asking me questions as well in the interviews about this and that and so that also forces me [to reflect]" (Interview, July 31, 2013).

Changes in the physics professor's conceptions, by reflection on his practices in the classroom (DP▪►PeD), were major stimulus of change. These included teaching MAT students. Professor Fairbanks remarked, "It changes then how you think about what you're doing because you're not just teaching them physics but you're modeling teaching" (Interview, June 5, 2012). Also, the change in his conceptions of teaching conceptual change from the "concrete to the abstract" linked to his reflecting on how students were learning about teaching conceptual change in the context of a worksheet (Interview, July 31, 2013).

Changes from reflection on the students' learning (DC) were visible in the physics professor's conceptions and confidence (DC▪►PeD). For example, the initial FCI results in the second year in Professor Fairbanks words, "changed my expectations of what we could accomplish" (Interview, July 10, 2013). Similarly, when Professor Fairbanks described what a successful discussion looked like, he stated, "I know the difference in me when I'm doing that [leading a successful discussion]….There wasn't the pressure to get through it and get onto something else" (Interview, July 10, 2013).

Change in practice.

Correspondingly, the IMTPG model showed three general processes led to change in the physics professor's practices: enactment from the external domain (ED→DP), enactment from the personal domain (PeD→DP), and enactment from the domain of consequence (DC→PeD). The change, resulting in the physics professor's practices during the science education professor's absence at the beginning of the second summer, was the most prolific example of an enactment from ED on DP changes. A negative case of this ED→PeD enactment on the professor's practice was the students' teaching in the studio classroom with the associated time pressure and the need to cover the material for their preparation leading to "a more didactic approach" (Interview, July 10, 2013).

Enactment from the PeD was prevalent and reflected the effect of the physics professor's conceptions on his practice. The common pattern observed was Professor Fairbanks' framework guiding his pedagogy. Professor Fairbanks summarized this as, "trying to model the right kind of approach" (Interview, July 31, 2013). As Professor Fairbanks' ideas on the approach to teaching conceptual change evolved so did his practice, but with a lagging effect. He expressed the ideas of applying the ideas of teaching for conceptual change to advanced physics classes and "getting their ideas out" (Interview, July 31, 2013). Yet, in the observations of his practice in the upper-level lab course, limited evidence was observed.

Changes from the enactment of DC centered on students' learning. Focusing on the goal of increasing the students' conceptual understanding, the physics professor enacted a general strategy of students completing the same exercises they would teach. His methods for this evolved into focusing on making the students' ideas visible and having the students see the implications of their ideas.

Growth networks.

As discussed in Chapter 4, the change in the physics professor's conceptions and practices, like in conceptual change, is a complex process with the interaction of many interconnected ideas forming a framework that must be modified for lasting change. The IMTPG identified these more complex changes, involving more than the interaction between two domains as change sequences. As these change sequences are repeated, growth networks are formed leading to more lasting change.

The central growth pattern observed involved (1) the ED enactment on the DP; (2) stimulating a reflection of the DP on the PeD; (3) leading to an enactment of the changed PeD on the DP. Breaking this down, Professor Fairbanks' observing Professor Crefeld's teaching on conceptual change in the classroom (ED→DP) led to Professor Fairbanks' broadening ideas of teaching from conceptual change (DP▪▶PeD). He progressed from primarily concrete application to more "robust understanding of conceptual change and conceptual change theory" (Interview, June 12, 2013). This enabled later change in Professor Fairbanks' practice (PeD→DP) realized in such changes as teaching conceptual change from the context of the activity and effectively leading moderated class discussions. Another example of this growth pattern, especially in the first year, was Professor Crefeld's modeling, of teaching for conceptual change with the students, overlapping with exercises Professor Fairbanks was doing (ED-DP). Professor Fairbanks recognized this (DP▪▶PeD) and began emphasizing the similarities and using the same conceptual change vocabulary (PeD→DP).

Another growth pattern present was a reflection of the DP on the DC (DP▪▶DC) leading to further reflection from the DC to the PeD (DC▪▶PeD) and then enactment in the DP (PeD→DP). Attempting to lead open-ended discussions shifted Professor Fairbanks' goals from covering the material to eliciting and valuing students' ideas in new ways (DP▪▶DC). Students' learning was tied in with "students being able to see conflicts in their ideas and resolve them" (Interview, June 12, 2013). Reflecting on this (DC▪▶PeD) Professor Fairbanks described his changed focus, "More on everything through that prism of a particular physics activity" (June 10, 2013). His understanding of how the activity matched up with the framework of teaching for conceptual change was used to drive the classroom discussions (PeD→DP). The difference in Professor Fairbanks' instruction on momentum between the two years was a dynamic example of this growth pattern.

The IMTPG provided a powerful framework for modeling the observed teacher change in Professor Fairbanks' conceptions and practices for conceptual change resulting from the collaboration. One aspect observed in this study, but not reflected in the IMTPG model, was the effect of Professor Fairbanks' practice on the rest of his department. Unique in this study was Professor Fairbanks' senior role in his department. His decisions and practices impacted beyond just his classroom. As Professor Fairbanks articulated on the requirement of teaching MAT students,

> You're not just teaching them physics, but you're modeling teaching. And so that I think [has] an impact on my teaching, but hopefully it will impact broader as it pervades…seeps into the [physics] department and department's psyche as to how classes are taught. (Interview, June 5, 2012)

Professor Fairbanks' decision, following his collaborative experience to resume instructing the upper-level lab course primarily because of the prior instructor's ineffective teaching, was one clear example of this change. This type of change would be better represented on the IMTPG as an enactment process of the DP on the ED (DP→ED). Figure 10 denoted this change with a bold arrow showing the proposed change.

As discussed in Chapter 2, teacher change is a process. The well-established CBAM's SoC instrument (Hall et al., 1998; Hord et al., 1987) was utilized to compare the physics professor's progress in adopting a teacher innovation (teaching for conceptual change). Both a pre- and post- survey showed a primary level of concern of awareness (Appendix G). This indicated the physics professor had other competing concerns on his mind besides teaching for conceptual change. These other concerns identified by the physics professor in his learning environments are discussed next.

Learning Environment Factors

The physics professor's self-efficacy manifested in his desire to improve student learning was a consistent motivating factor behind his change. This influence was evident in his adopting PER in his classroom, transitioning into educational research, taking on the role of undergrad advisor, and in this collaboration with the science education professor. This aligned with other studies that showed instructors' willingness to try new teaching methods, tied to their desire to improve student learning along with a dissatisfaction with their current methods (Briscoe & Prayaga, 2004; Dancy et al., 2010; Pundak, Rozner, Yacobson, & Toledano-Kitay, 2008). The initial exposure of the physics professor to conceptual change through PER and his limited success in implementing PER methods within his classroom prior to the collaboration correlated with several PER dissemination studies' findings of high awareness, but relatively low implementation among faculty (Dancy et al., 2010; Henderson, 2012; Henderson et al., 2012).

The pattern of the physics professor reverting back to traditional methods of instructing because of time pressure aligned with a common finding that time was the biggest self-identified hindrance to change (Bakkenes, Vermunt, & Wubbels, 2010; Beichner et al., 2007; Besterfield-Sacre et al., 2014; Dancy et al., 2010; Massy et al., 1994; Prince, Borrego, Henderson, Cutler, & Froyd, 2013; Seymour, DeWelde, & Fry, 2011; Van Eekelen, Boshuizen, & Vermunt, 2005). Other studies pointed out a tendency of novice teachers to revert back to traditional methods when stress was experienced (Borrego, Cutler, Prince, Henderson, & Froyd, 2013; Pundak et al., 2008; Trigwell, 2012). Additional studies linked this to an unwillingness to take risk and reverting to the safety of teacher-focused methods (Boice, 1991; Geoghegan, 1994; Trigwell, 2012).

The collaboration with the science education professor was the main facilitator of change on the physics professor's conceptions and teaching for conceptual change. Other studies have shown collaboration with colleagues as the principle way physics teachers learn of research-based instruction (Dancy et al., 2010), the most effective means of diffusion of change (Borrego & Henderson, 2014; Prince et al., 2013), and influential in changing beliefs (Bailey & Nagamine, 2012; Briscoe & Prayaga, 2004; Henderson et al., 2009). Similar studies of collaborations between an expert instructor and a physics professor revealed similarities in the development of common language, trust between the participants, and a mutual respect for each other's expertise (Briscoe & Prayaga, 2004; Henderson et al., 2009).

The extended collaboration studied closely resembled the model of co-teaching where two teachers work together with a group of students sharing the responsibilities of teaching the class (Bacharach et al., 2007). The co-teaching did help the physics professor become a better teacher in teaching for conceptual change (Bacharach et al., 2007; Roth & Tobin, 2004). Key characteristics of the co-teaching involved being established on a foundation of professional trust and respect between both parties. This collaboration was between two experts who mutually respected each other, chose to work together, and learn from each other collegiately. It is important to note that each professor acknowledged the expertise of the other professor (e.g., physics content vs. pedagogy). Additionally, it was notable to observe each professor when acting as the lead teacher, modeling and explicitly sharing his rationale behind the instruction (e.g., Professor Crefeld teaching for conceptual change) (Bacharach et al., 2010). These were important distinctions of this co-teaching from other co-teaching studies of science teachers, already discussed which involved two teachers of differing experience levels (Henderson et al., 2009) or limited experience (Bailey & Nagamine, 2012). In the context of this study, the focus was on the expertise of the science education professor in teaching for conceptual change rather than the expertise of the physics professor in teaching physics content.

As pointed out, the progression of this collaboration (initial collaboration preceding a period of independent practice followed by a resumed collaboration) was a key factor in facilitating a more fundamental change in the physics professor. The initial modeling by the expert was essential in helping make the tacit, context-dependent knowledge of the expert understandable to the physics professor (Bailey & Nagamine, 2012; Henderson et al., 2009). The physics professor's adopting a "concrete to abstract" approach, when independently teaching for conceptual change, matched a pattern of novices adopting more concrete innovations and changing them more toward traditional means (Henderson et al., 2009; Seymour et al., 2011). The physics professor's struggling with implementing teaching for conceptual change independently was consistent with findings that showed lack of faculty support during the trial stage of implementing change as a major barrier to lasting change (Borrego & Henderson, 2014; Pundak et al., 2008).

A powerful stage in the observed changes of the physics professor was the resumed collaboration following the independent practice. This allowed the physics professor to further develop his understanding and practice of teaching for conceptual change, focusing on specific areas of confusion or struggle he experienced during his independent practice. The additional instruction and modeling helped prevent him from inappropriately assimilating teaching for conceptual change, a result often seen with novices regarding change innovations (Borrego & Henderson, 2014; Henderson & Dancy, 2007; Yerrick, Parke, & Nugent, 1997). This resumed collaboration following a period of independent practice appeared to be a unique feature in this study not replicated in similar collaboration studies. Another unique aspect of this collaboration was its two-year duration. While this is a common recommendation in the literature, successful change strategies have typically involved efforts over an extended period of time, but few studies have extended beyond a semester (Gallos, Berg, & Treagust, 2005; Gibbs & Coffey, 2004; Henderson et al., 2009; Henderson et al., 2011; Ho et al., 2001; Pundak et al., 2008).

As modeled in the IMTPG, the external domain outside the classroom exerted a significant influence on the extent of change within the physics professor's conceptions and practices. Both departmental and institutional cultures and policies played an important role in both the facilitating and resistance to change (Besterfield-Sacre et al., 2014; Fairweather, 2008; Prosser & Trigwell, 1999; Seymour et al., 2011; D. W. Sunal et al., 2001). With the departmental and institutional culture, the physics professor's senior position was vital in establishing the collaboration and ensuring the resulting change extended beyond just the PHYS 7050 class. This matched prevalent recommendations within the literature of the importance in the change process of engaging senior faculty members with power and influence (Fairweather, 2008; Merton, Clark, Richardson, & Froyd, 2001; Seymour et al., 2011). The established change initiatives in the physics professor's department and the expanding number of faculty in educational research support the importance of increased collegiality and need for faculty learning communities for sustained change (Borrego & Henderson, 2014; Fairweather, 2008; Henderson et al., 2008; Massy et al., 1994; D. W. Sunal et al., 2012; Van Eekelen et al., 2005). The requirement of outside funding in developing and providing release time for the collaboration was very common and often a hindrance for establishing lasting change initiatives (Fairweather, 2008; Seymour et al., 2011). The university's tenure and reward structure, prioritizing research over teaching mentioned by the physics professor, was a barrier frequently highlighted by studies on change initiatives (Fairweather, 2005, 2008; Massy et al., 1994; Seymour et al., 2011).

The learning environment's characteristics identified by the physics professor as both facilitating and hindering change were found to be well-established in the literature on change in STEM disciplines. Many of the characteristics of the collaboration aligned with past recommendations of other studies, such as a prolonged collaboration and the inclusion of senior faculty members. Unique to this collaboration, though, was its progression of an initial collaboration, preceding an independent practice, and followed by a resumed collaboration. The extent of this and other factors are discussed now in regard to the overarching research question.

Overarching Research Question

Figure 11 provides an overview of how a physics professor conceptualized and practiced teaching for conceptual change during and beyond an extended collaboration with a science education professor. The top row shows the emergent categories of teaching for conceptual change in a hierarchical arrangement from left to right. Below this enclosed by an arrow are the conceptions of teaching for conceptual change identified with each category.

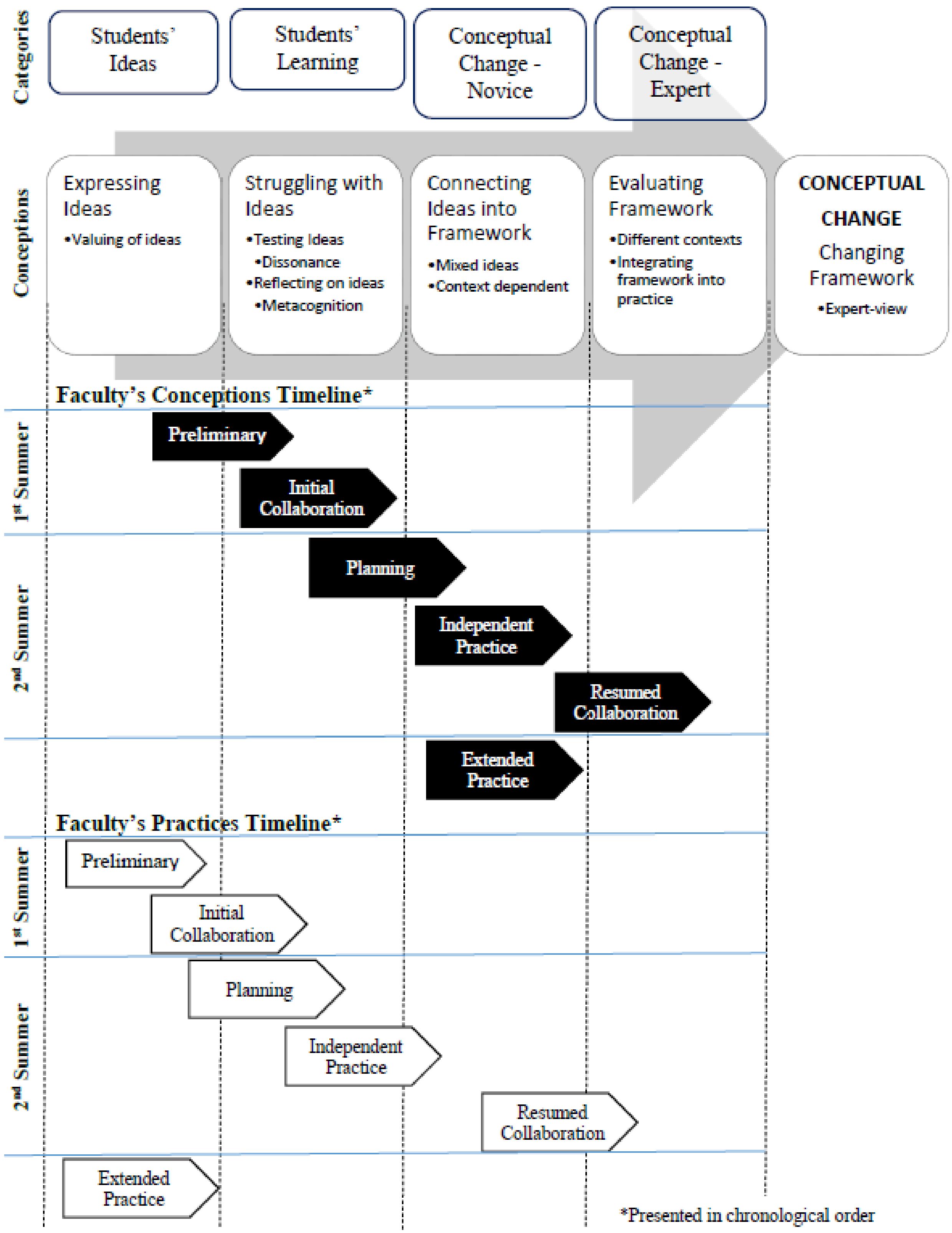


Figure 11. Change Timeline of Physics Professor's Conceptions and Practices

As discussed, a progression was seen from valuing of students' ideas to students' evaluating and changing their frameworks, consistent with a teaching for conceptual change framework (Hewson et al., 1998). The solid black arrows below this indicate the timeline of the physics professor's conceptions which is followed by the timeline of the physics professor's practices.

Timeline for changes in conceptions.

Initially, heavily influenced by PER, the physics professor's conceptions lay between the Students' Ideas and Students' Learning categories. Through the influence of the science education professor's instruction and modeling during the initial collaboration, the physics professor's conceptions shifted fully into the Students' Learning category. A slight movement toward the Conceptual Change – Novice category occurred during the planning period. The physics professor planned the second-year course independently requiring a greater integration of a conceptual change framework with the specific pedagogy of the course. The following independent practice showed a significant shifting of the physics professor's conceptions fully into the Conceptual Change – Novice category. The pressure to teach the conceptual change framework, along with the physics content, required greater reflection and risk taking on the physics professor's part. The greatest change in the physics professor's conceptions occurred in the resumed collaboration with the science education professor. A significant shifting of the physics professor's conceptions into the Conceptual Change – Expert category was noted. Returning to teaching with the expert provided a safe environment for the physics professor to refine and further develop ideas and methods he had struggled with independently. In the extended practice of the upper-level lab course, the physics professor exhibited an ability to adapt his conceptions of teaching for conceptual change to a different context, but with limitations.

Timeline for changes in practices.

A similar pattern with some distinctive differences was seen in the physics professor's timeline of the changes in his practice. The physics professor's practices consistently lagged behind his conceptions of teaching for conceptual change (Borrego, Froyd, & Hall, 2010; Trigwell & Prosser, 1996; Vermunt & Endedijk, 2011). The first major change in the physics professor's conceptions followed the initial collaboration. The physics professor often attempted to link his instruction with the science education professor's teaching and modeling during this period.

The next major change corresponded to the period of independent practice. During this period, the physics professor attempted to emulate the teaching of the science education professor that he had observed the year before. While significant change resulted, the practices adopted by the physics professor reflected modifications toward more traditional methods (Henderson et al., 2009; Seymour et al., 2011).

The greatest change in the physics professor's practices was observed during the resumed collaboration. Both emulation and assimilation of the methods of the science education professor were observed in the physics professor. A more expert framework in teaching for conceptual change was exhibited by the physics professor by his ability to integrate a conceptual change framework into specific activities.

The biggest difference between the physics professor's conceptions and practice was noted in the extended period. Teaching in a different context, the physics professor's practice showed predominately traditional methods with expressed ideas of conceptual change in the planning of the course and limited elements of teaching for conceptual change. The biggest restraint noted was the drastic difference in aims of PHYS 3000 and PHYS 7050, a limitation of the study.

Incremental change was apparent in both the physics professor's conceptions and practices throughout the collaboration. A consistent pattern of the physics professor's practices trailing behind his conceptions was identified as found in the literature (Borrego et al., 2010; Trigwell & Prosser, 1996; Vermunt & Endedijk, 2011). The significant difference between the physics professor's conceptions and practices in the upper-level lab course was noteworthy. A larger difference was noted in the physics professor's practice than in his conceptions in this different learning environment. Yet, the distinctive differences in the context and aim of PHYS 3000 obscured any clear interpretation of the carryover of the physics professor's conceptions and practices to this context. The larger change in the physics professor's practices compared with his conceptions during the resumed collaboration pointed to changes in practices being more dependent on the support of an expert. This finding, coupled with the limited change in practices in the absence of the expert, strongly suggested a connection between changes in practice and expert support.

Overall, there was evidence of fundamental change. However, the difficulty exhibited by the physics professor in teaching for conceptual change on his own and in different contexts, especially in practices, pointed to limited change within a novice and not the full transforming change of an expert. The key findings, implications, and recommendations stemming from the physics professor's change are considered next.

Conclusions

In this study on the collaboration between a physics professor and science education professor, measurable change was documented in the physics professor's conceptions and practices of teaching for conceptual change. The physics professor's framework of teaching for conceptual change developed from initially valuing students' ideas and seeking to expose these ideas which differed from scientific conceptions. His framework changed into a more sophisticated view of students' ideas interconnecting into frameworks, and his teaching conceptions focused on students' metacognitevly evaluating these frameworks in different contexts and in relationship to scientific phenomena. The physics professor's methods for teaching for conceptual change evolved slower, requiring more expert modeling and explicit instruction to change. A shifting in the physics professor's use and mastery of moderated class discussion, driven by students' ideas, focused on building and evaluating explanatory frameworks of science conceptions and emerged at the end of the collaboration.

The progression of the collaboration, with a period of initial expert instruction and modeling preceding a period of independent practice followed by a resumed period of explicit expert modeling, was essential to the physics professor's assimilation of the concepts and practices of teaching for coneptual change into his instruction. This study identified critical aspects of this progression: the initial exposure to an expert framework followed by a period where the physics professor was forced to attempt to independently emulate the expert's modeling; the modification of the expert's techniques by the physics professor to fit his personal style through a metacognitive approach to pedagogy; and the resumed explicit modeling, providing guidance and safety to the physics professor to reaccess and further develop his framework and practices.

Limitations to the change in the physics professor's conceptions and practices were connected to a need for a safety zone to attempt change. The collegiality of the co-teaching provided a safe enviroment for the physics professor to explore and try out new ideas and practices. During the absence of the expert, time pressure for content coverage and preparing students inhibited the change and resulted in an expressed lack of confidence.

Significance for Other Research

In chapter 2, collaborations between College of Sciences and College of Education were identified as key factors in improving undergraduate science and science teacher training. Yet, rigorous studies of the effect of these collaborations were rare. Studies of co-teaching between an expert educator and an expert scientist, though recommended, were also lacking. This study provided empirical evidence for both a collaboration between science and education departments and more specifically between education and science faculty members.

The study further extends the work of other phenomenological studies on teachers' conceptions on teaching and learning to include a connection between both a teacher's conceptions and practices (Akerlind, 2004; McKenzie, 2003). Phenomenological studies typically rely solely on interviews for their data, which is a common criticism of the methodology (J. T. E. Richardson, 1999; Sin, 2010). This study extended the phenomenography method to include data from the observed practice of the physics professor. By recording the classes, the physics professor's own words used during his practice were analyzed. This provided consistency with the phenomenography methodology, being a "second order perspective" examining the learner's experience as he or she expresses it (Marton & Booth, 1997; Svensson, 1997). Using recorded observations was something lacking in similar phenomenography studies.

Lack of direct observation of change in the classroom was a weakness found in the literature on teacher change resulting from collaboration (Ballone-Duran et al., 2005; Clifford et al., 2008). This study again provided empirical evidence directly from the classroom of observed change resulting from collaboration.

Reforming STEM education is a national priority (PCAST, 2012). Nevertheless, the literature on how to promote change in instructional practice is characterized by studies lacking strong evidence to support their claims and a general need for work building on prior empirical and theoretical work (Henderson et al., 2011). Additional recommendations within this literature include studies involving collaboration, long-term interventions, and senior faculty members (Henderson et al., 2011; Seymour et al., 2011). This study addressed these needs by providing empirical data on the change in a senior physics faculty member, resulting from a two-year collaboration on the well-established theoretical framework of teaching for conceptual change.

Another insight gained from the study involving a senior faculty member was the impact of this faculty member's practice in the classroom on the broader departmental environment. This development led to the recommendation to extend the IMTPG model (Clarke & Hollingsworth, 2002) to include an additional enactment path from the DP→ED, linking the change that occurred in the faculty member's practices in the classroom to subsequent changes in the department. Overall, the study validated and extended the IMTPG model, demonstrating its robustness in providing a framework for complex teacher change in a very specific setting.

Implications

In the current environment of reforming undergraduate education, facilitating change of established faculty members from traditional teaching methods to more research-based teaching methods is a significant challenge. The hope is that this study, which demonstrated this change in one senior physics professor through a collaboration with an education professor, would encourage additional initiatives and further research in how to facilitate this on a broader scale.

From this study, several key insights into collaboration emerged. First, the relationship between the collaborators strongly influenced the effect. The strong collegiality of this collaboration, marked by mutual respect and openness to new ideas, provided a safe environment for the members to work through new ideas and support each other in this endeavor. Secondly, an external pressure was needed to propel the physics professor through the barriers created by his lack of confidence into implementing change on his own. In this study, the structure of the class, requiring both the teaching of content and pedagogy focused on teaching for conceptual change, provided this pressure. Thirdly, a second period of collaboration following independent practice helped the physics professor overcome barriers to his implementation of the change, thus revising more traditional changes. It is important to note that this collaborative pattern emerged from the circumstances of the study and not the initial design. Research into a collaboration intentionally designed with this distinct progression is needed for further confirmation.

The role of the expert in assisting the facilitation of change was an important finding. Independent change was limiting, often stymied by a lack of confidence and external pressures. Expert guidance through explicit instruction and modeling was needed to progress. This supports the idea of learning communities where experts from different fields such as teaching, research, and science meet to improve teaching and learning. It also underscores the importance of personal collaboration and mentoring.

Change is a very slow and gradual process. The pace of change in the physics professor's background and the limited carryover of the change to other contexts demonstrated this. One of the central challenges is the transition from a novice to an expert and the need of expert support through this process.

External barriers and internal motivation are common roadblocks in the change process. These external barriers are often found in institutional and departmental norms and cultures. While our study showed how a senior, highly motivated professor could circumvent many of these obstacles, it is important to note that even this required external funding and the extensive interaction with an educational expert to achieve the change documented. External initiatives at the university level (PRISM) and changes within the physics department (SCALEUP, PER professor) laid the groundwork for this collaboration to develop. Institutional policy and agendas do matter. Initiatives that encourage faculty scholarship work are important in facilitating change in college science teaching. A broad implication from this is that an environment of change spawns more change.

Limitations

As detailed, this study was very unique involving one senior physics professor teaching in a specific course designed to teach future physics teachers in an extended collaboration with a science education professor. The aim of this study is that the depth of detail of the professor, the collaboration, and the physics professor's conceptions and practices will give insight into the process of change. The ability to directly translate these specific findings to a larger context is limited. While the observations in PHY 3000 provided some context, the extent to which the change translated in the physics professor's practice outside of PHYS 7050 is incomplete. The observation was hampered by the drastic, different aims of the class. Looking at the change in several different environments such as an introductory physics course and an upper-level physics course with similar aims as the PHYS 7050 would be more insightful. The length of study, while substantially longer than most, still proved somewhat limited in ascertaining the effect of the changes observed. Would the changes have an increasing effect of the physics professor's conceptions and practices leading to further change, or would it be a fading effect with a return to traditional methods over time? These are important questions where further research would be helpful in answering.

Recommendations

As this study demonstrated, collaboration can be a powerful tool for teacher change. The significant effect of an expert on change requires more mentoring and collaborative efforts. To a greater extent collaborations need to be promoted especially those that combine expert knowledge of science, teaching, and research disciplines. Co-teaching, as an effective means for this, should be more readily utilized. Barriers to collaboration are substantial and continued effort is needed to provide a more supportive environment including a university rewards system which does not prioritize research over teaching. Universities need to encourage cooperation across departments and provide time and support for faculty members involved in collaborations. Policy changes, which encourage faculty scholarship, lower barriers between departments, encourage collaboration and foster a climate of change, are needed. One way to initiate change within the departmental environment is involving senior faculty members with their broader field of influence.

Future research needs to aid in more fully understanding collaboration. Specific aspects from this collaboration that could benefit from deeper investigations to understand: (1) the positive change resulting from the specific three stage progression of collaboration; (2) the role of the expert in changing practices; and (3) longitudinal studies focused on the lasting or diminishing effect of teacher change.

In the broader scope, STEM initiatives to reform undergraduate science education must impact the training of science teachers. Classes, like PHYS 7050, combining expert content and pedagogy, are essential to producing teachers who can more effectively teach science and produce sustainable change within their science classrooms. The lasting impact of teacher change must be improved students' learning. When that learning involves how to more effectively teach science, it is a powerful thing. Professor Fairbanks' changes in his instruction in PHYS 7050 has that potential. Sophia, one of the MAT students, expressed the immediate impact on PHYS 7050 on her conceptions of physics teaching. She reflected,

> I think I was able to understand more of what I was thinking, what I was anticipating, what I already knew and just a better idea, a gauge of where I'm at. Because I really came into this [with an] idea of if and when I have to teach physics, it's going to just be very direct instruction. But this really gave me, a whole set of different tools that I can pull from, with literature to read from and just setting up your classroom in a more collaborative-type setting….We were students in this setting, so it brought more of an opportunity to be able to identify more with the student when roles are reversed and I'm the teacher. (Student Interview, July 25, 2013)

REFERENCES

Akerlind, G. S. (2004). A new dimension to understanding university teaching. *Teaching in Higher Education, 9*(3), 363-375.

Akerlind, G. S. (2007). Constraints on academics' potential for developing as a teacher. *Studies in Higher Education, 32*(1), 21-37.

Akerlind, G. S. (2008). A phenomenographic approach to developing academics' understanding of the nature of teaching and learning. *Teaching in Higher Education, 13*(6), 633-644.

Akerlind, G. S. (2012). Variation and commonality in phenomenographic research methods. *Higher Education Research and Development, 31*(1), 115-127.

Anderson, C. W. (2007). Perspectives on science learning. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 3-30). Mahwah, NJ: Lawrence Erlbaum Associates.

Anderson, S. E. (1997). Understanding teacher change: Revisiting the concerns based adoption model. *Curriculum Inquiry, 27*(3), 331-367.

Anderson, W. A., Banerjee, U., Drennan, C. L., Elgin, S. C. R., Epstein, I. R., Handelsman, J., . . . Warner, I. M. (2011). Changing the culture of science education at research universities. *Science, 331*, 152-153.

Andrews, J., Garrison, D. R., & Magnusson, K. (1996). The teaching and learning transaction in higher education: A study of excellent professors and their students. *Teaching in Higher Education, 1*, 81-103.

Austin, A. E. (2002). Preparing the next generation of faculty: Graduate school as socialization to the academic career. *The Journal of Higher Education, 73*(1), 94-112.

Austin, A. E. (2003). Creating a bridge to the future: Preparing new faculty to face changing expectations in a shifting context. *The Review of Higher Education, 26*(2), 119-144.

Bacharach, N., Heck, T. W., & Dahlberg, K. (2007). Co-teaching in higher education. *Journal of College Teaching and Learning, 4*, 19-26.

Bacharach, N., Heck, T. W., & Dahlberg, K. (2010). Changing the face of student teaching through coteaching. *Action in Teacher Education*, *32*(1), 3-14.

Bailey, J. M., & Nagamine, K. (2012). Experiencing conceptual change about teaching: A case study from astronomy. *American Journal of Physics, 80*(6), 542-551.

Bakkenes, I., Vermunt, J. D., & Wubbels, T. (2010). Teacher learning in the context of educational innovation: Learning activities and learning outcomes of experienced teachers. *Learning and Instruction*, *20*(6), 533-548.

Ball, D. L., Thames, M. H., & Phelps, G. (2008). Content knowledge for teaching: What makes it special? *The Journal of Teacher Education*, *58*(5), 389-407.

Ballone-Duran, L., Czerniak, C. M., & Haney, J. J. (2005). A study of the effects of a LSC project on scientists' teaching practices and beliefs. *Journal of Science Teacher Education, 16*, 159-184.

Barinaga, M. (1991). Scientists educate the science educators. *Science, 252,* 1061-1062.

Becker, H. S. (1996). The epistemology of qualitative research. In R. Jessor, A. Colby, & R. A. Shweder (Eds.), *Ethnography and human development: Cotext and meaning in social inquiry* (pp. 53-71). Chicago, IL: University of Chicago Press.

Beeth, M. E., & Hewson, P. W. (1999). Learning goals in an exemplary science teacher's practice: Cognitive and social factors in teaching for conceptual change. *Science Education, 83*, 738-760.

Beichner, R. J. (2008). *The SCALE-UP Project: A student-centered, active learning environment for undergraduate programs.* Paper presented at the BOSE Conf. Promis. Pract. - Innov. Undergrad. STEM Educ., Washington, DC.

Beichner, R. J., Saul, J. M., Abbott, D. S., Morse, J. J., Deardorff, D. L., Allain, R. J., . . . Risley, J. S. (Eds.). (2007). *The Student-centered activities for large enrollment undergraduate programs (SCALE-UP) project*. College Park, MD: American Association of Physics Teachers.

Bergquist, W. H., & Pawlak, K. (2008). *Engaging the six cultures of the academy*. San Francisco, CA: Jossey-Bass.

Besterfield‐Sacre, M., Cox, M. F., Borrego, M., Beddoes, K., & Zhu, J. (2014). Changing engineering education: Views of US faculty, chairs, and deans. *Journal of Engineering Education, 103*(2), 193-219.

Biggs, J., & Tang, C. (2011). *Teaching for quality learning at university* (4th ed.). Berkshire, England: Open University Press.

Billett, S. (1996). Situated learning: Bridging sociocultural and cognitive theorising. *Learning and Instruction, 6*(3), 263-280.

Bogdan, R. C., & Biklen, S. K. (2006). *Qualitative research for education: An introduction to theories and methods* (5th ed.). Boston, MA: Allyn and Bacon, Inc.

Boice, R. (1991). New faculty as teachers. *The Journal of Higher Education, 62*(2), 150-173.

Booth, S. (1997). On phenomenography, learning and teaching. *Higher Education Research and Development, 16*(2), 135-158.

Booth, S., & Hulten, M. (2003). Opening dimensions of variation: An empirical study of learning in a web-based discussion. *Instructional Science, 31*, 65-86.

Borkan, J. (1999). Immersion/Crystallization. In B. F. Crabtree & W. L. Miller (Eds.), *Doing qualitative research* (pp. 179-194). Thousand Oaks, CA: Sage.

Borko, H. (2004). Professional development and teacher learning: Mapping the terrain. *Educational Researcher, 33*(8), 3-15.

Borrego, M., Cutler, S., Prince, M., Henderson, C., & Froyd, J. E. (2013). Fidelity of Implementation of Research - Based Instructional Strategies (RBIS) in Engineering Science Courses. *Journal of Engineering Education, 102*(3), 394-425.

Borrego, M., Froyd, J. E., & Hall, T. S. (2010). Diffusion of engineering education innovations: A survey of awareness and adoption rates in US engineering departments. *Journal of Engineering Education, 99*(3), 185-207.

Borrego, M., & Henderson, C. (2014). Increasing the use of evidence - based teaching in STEM higher education: A comparison of eight change strategies. *Journal of Engineering Education, 103*(2), 220-252.

Bouwma-Gearhart, J. (2012). *Engaging STEM faculty while attending to professional realities: An exploration of successful postsecondary STEM education refrom at five science & mathematics teacher imperative institutions*. Retrieved from Washington, DC: http://www.aplu.org/document.doc?id=4101

Boyer, E. L. (1990). *Scholarship reconsidered: Priorities of the professoriate.* Lawrenceville, NJ: Princeton Universtiy Press.

Boyer, E. L. (1991). The scholarship of teaching from scholarship reconsidered: Priorities of the professoriate. *College Teaching, 39*(1), 11-13.

Bransford, J. D., Brown, A. L., & Cocking, R. R. (Eds.). (2000). *How people learn: Brain, mind, experience, and school*. Washington, DC: National Academy Press.

Brantley-Dias, L., Calandra, B., Harmon, S. W., & Shoffner, M. B. (2006). An analysis of collaboration between colleges of education and arts & sciences in PT3. *TechTrends, 50*(3), 32-37.

Brew, A. (2006). *Research and teaching: Beyond the divide*. New York, NY: Palmgrave Macmillan.

Briscoe, C., & Peters, J. (1997). Teacher collaboration across and within schools: Supporting individual change in elementary science teaching. *Science Education, 81*, 51-66.

Briscoe, C., & Prayaga, C. (2004). Teaching future K-8 teachers the language of Newton: A case study of collaboration and change in university physics teaching. *Science Education, 88*, 947-969.

Brown, D. E. (2014). Students' conceptions as dynamically emergent structures. *Science & Education, 23*(7), 1463-1483.

Brown, D. E., & Hammer, D. (2008). Conceptual change in physics. In S. Vosniadou (Ed.), *International Handbook of Research on Conceptual Change* (pp. 127-154). New York, NY: Routledge.

Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher, 18*(1), 32-42.

Brownell, S. E., & Tanner, K. D. (2012). Barriers to faculty pedagogical change: lack of training, time, incentives, and… tensions with professional identity? *CBE-Life Sciences Education*, *11*(4), 339-346.

Burnes, B. (2004). Kurt Lewin and the planned approach to change: A re-appraisal. *Journal of Management Studies, 41*(6), 977-1002.

Bybee, R. W., & Fuchs, B. (2006). Preparing the 21st century workforce: A new reform in science and technology education. *Journal of Research in Science Teaching, 43*(4), 349-352.

Chasteen, S. V., Pepper, R. E., Pollock, S. J., & Perkins, K. K. (2012). But does it last? Sustaining a research-based curriculum in upper-division electricity & magnetism. *AIP Conference Proceedings, 1413*, 139-142.

Chasteen, S. V., & Pollock, S. J. (2012). Thinking like a physicist: A multi-semester case study of junior-level electricty and magnetism. *American Journal of Physics, 80*(10), 923-930.

Chi, M. (2008). Three types of conceptual change: Belief revision, mental model transformation, and categorical shift. In S. Vosniadou (Ed.), *International Handbook of Research on Conceptual Change* (pp. 61-82). New York, NY: Routledge.

Chi, M., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5*, 121-152.

Chi, M., Slotta, J. D., & de Leeuw, N. (1994). From things to processes: A theory of conceptual change for learning science concepts. *Learning and Instruction, 4*, 27-43.

Clarke, D., & Hollingsworth, D. (2002). Elaborating a model of teacher professional growth *Teaching and Teacher Education, 18*, 947-967.

Clement, J. (1993). Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics. *Journal of Research in Science Teaching, 30*(10), 1241-1257.

Clifford, M., Millar, S. B., Smith, Z., Hora, M., & DeLima, L. (2008). *K-20 partnerships: Literature review and recommendations for research.* Retrieved from http://scalemsp.wceruw.org/files/research/Products/partnership_literature_review.pdf

Cobb, P., Wood, T., & Yackel, E. (1990). Classrooms as learning environments for teachers and researchers. In R. B. Davis, C. A. Mayer, & N. Noddings (Eds.), *Constructivist view on the teaching and learning of mathematics* (pp. 125-146). Reston, VA: National Council of Teachers of Mathematics.

Coffin, C. (2002). *Touching the future: Final report*. Retrieved from Washington, DC: http://www.acenet.edu/news-room/Documents/Touching-the-Future-Final-Report-2002.pdf

Cohen, A. M. (1998). *The shaping of American higher education: Emergence and growth of the contemporary system*. San Francisco, CA: Jossey-Bass.

Cohen, D. K. (1988). *Teaching practice: Plus a change*. East Lansing, MI: Michigan State University, National Center for Research on Teacher Education.

Cohen, D. K., & Hill, H. C. (2000). Instructional policy and classroom performance: The mathematics reform in California. *Teachers College Record, 102*(2), 294-343.

Cohen, L., Manion, L., & Morrison, K. (2000). *Research methods in education* (5th ed.). London: Routledge Falmer.

Collier-Reed, B., & Ingerman, A. (2013). Phenomenography: From critical aspects to knowledge claim. *Theory and Method in Higher Education Research, 9*, 243-260.

Collins, A. (2006). Cognitive Apprenticeship. In R. K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Science* (pp. 47-60). New York, NY: Cambridge University Press.

Cook, L., & Friend, M. (1995). Co-teaching: Guidelines for creating effective practices. *Focus on exceptional children, 28*(3), 1-17.

Creswell, J. W. (2003). *Research Design: Qualitative, quantitative, and mixed methods approaches* (2nd ed.). Thousand Oaks, CA: Sage Publications.

Crotty, M. (1998). *The foundations of social research: Meaning and perspective in the research process*. London: Sage Publications.

Cuban, L. (1990). Reforming again, again, and again. *Educational Researcher, 19*(1), 3-13.

Dahlgren, L. (1997). Learning conceptions and outcomes. In F. Marton, D. Hounsell, & N. Entwistle (Eds.), *The experience of learning: Implications for teaching and studying in higher education* (2nd ed., pp. 23-38). Edinburgh, UK: Scottish Academic Press.

Dall'Alba, G. (1991). Foreshadowing conceptions of teaching. In B. Ross (Ed.), *Research and development in higher education* (Vol. 13). Sydney, Australia: Higher Education Research and Development Society of Australasia, Problem-based Learning Assessment Research Centre.

Dancy, M. H., Turpen, C., Henderson, C., Singh, C., Sabella, M., & Rebello, S. (2010). *Why do faculty try research based instructional strategies?* Paper presented at the AIP Conference Proceedings.

Darling-Hammond, L. (2006). Constructing 21st-century teacher education. *Journal of Teacher Education, 57*(3), 300-314.

Darling-Hammond, L. (2010). Teacher education and the American future. *Journal of Teacher Education, 61*(1-2), 35-47.

Darling-Hammond, L., Wise, A. E., & Klein, S. P. (1995). *A license to teach: Building a profession for the 21st century*. Boulder, CO: Westview Press.

Demir, K., Czerniak, C. M., & Hart, L. C. (2013). Implementing Japanese lesson study in a higher education context. *Journal of College Science Teaching, 42*(4), 32-37.

Demir, K., & Ellett, C. D. (2014). Cross-cultural research and perspectives on epistemology, learning environments, and culture. In R. Evans, J. Luft, C. Czemiak, & C. Pea (Eds.), *The role of science teachers' beliefs in international classrooms; from teacher actions to student learning* (pp. 65-79). The Netherlands: Sense Publishers.

Demir, K., Sutton-Brown, C., & Czerniak, C. M. (2012). Constraints to changing pedagogical practices in higher education: An example from Japanese lesson study. *International Journal of Science Education, 34*(11), 1709-1739.

Denzin, N. K. (1989). *The research act: A theoretical introduction to sociological methods* (3rd ed.). Thousand Oaks, CA: Sage.

Denzin, N. K., & Lincoln, Y. S. (2000). Introduction: The discipline and practice of qualitative research. In N. K. Denzin & Y. S. Lincoln (Eds.), *Handbook of qualitative research* (2nd ed., pp. 1-28). Thousand Oaks, CA: Sage Publications, Inc.

Desimone, L. M. (2009). Improving impact studies of teachers' professional development: Toward better conceptualization and measures. *Educational Researcher, 38*(3), 181-199.

Desimone, L. M., Porter, A. C., Garet, M. S., Yoon, K. S., & Birman, B. F. (2002). Effects of professional development on teachers' instruction: Results from a three-year longitudinal study. *Educational Evaluation and Policy Analysis, 24*(2), 81-112.

Dewalt, K. M., & Dewalt, M. R. (2002). *Participant observation: A guide for fieldworkers*. New York, NY: AltaMira Press.

diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction, 10*, 105-225.

diSessa, A. A. (2008). A bird's-eye view of the "pieces" vs. "coherence" controversy (from the "pieces" side of the fence) In S. Vosniadou (Ed.), *International Handbook of Research on Conceptual Change* (pp. 35-60). New York City, NY: Routledge.

Dole, J. A., & Sinatra, G. M. (1998). Reconceptualizing change in the cognitive construction of knowledge. *Educational Psychologist*, *33*, 109-128.

Driver, R., & Scott, P. H. (1996). Curriculum development as research: A constructivist approach to science curriculum development and teaching. In D. F. Treagust, R. Duit, & B. J. Fraser (Eds.), *Improving teaching and learning in science and mathematics* (pp. 94-108). New York, NY: Teachers College Press.

Druger, M., & Allen, G. (1998). A study of the role of research scientists in K-12 science education. *The American Biology Teacher, 60*(5), 344-349.

Dufresne, R. J., Gerace, W. J., Hardiman, P. T., & Mestre, J. P. (1992). Constraining novices to perform expertlike problem analysis: Effects on schema acquisition. *The Journal of Learning Sciences, 2*(3), 307-331.

Duit, R. (2009). Bibliography- STCSE. Students' and teachers' conceptions and science education. Retrieved from http://www.ipn.uni-kiel.de/aktuell/stcse/

Duit, R., & Treagust, D. F. (2012). How can conceptual change contribute to theory and practice in science education? In B. J. Fraser, K. G. Tobin, & C. J. McRobbie (Eds.), *Second international handbook of science education* (pp. 107-118). Dordrecht, The Netherlands: Springer.

Duran, L. B., McArthur, J., & Van Hook, S. (2004). Undergraduate students' perceptions of an inquiry-based physics course. *Journal of Science Teacher Education, 15*(2), 155-171.

Ebert-May, D., Derting, T. L., Hodder, J., Momsen, J. L., Long, T. M., & Jardeleza, S. E. (2011). What we say is not what we do: Effective evaluation of faculty professional development programs. *BioScience, 67*(7), 550-558.

Eble, K. E. (1972). *Professors as teachers*. San Francisco, CA: Jossey-Bass.

Eisner, E. W. (1991). *The enlightened eye: Qualitative inquiry and the enhancement of educational practice*. New York, NY: Macmillan Publishing Company.

Ellett, C. D. (2009). *Reformed Teaching Observation Protocol (RTOP): Annotated Form (6th. Revision)*. University System of Georgia, Board of Regents, Partnership for Reform in Science and Mathematics (PRISM Phase I).

Ellett, C. D., Monsaas, J., Martin-Hansen, L., & Demir, A. (2012). Development and validation of a new measure of faculty assessments of reformed teaching and learning practices. *The Journal of General Education, 61*(4), 388-405.

Ellsworth, J. B. (2000). *Surviving change: A survey of educational change models.* Syracuse, NY: Educational Resources Information Center.

Elmore, R. F. (1996). Getting to scale with good educational practice. *Harvard Educational Review, 66*(1), 1-26.

Entwistle, N. (1997). Contrasting perspectives on learning. In F. Marton, D. Hounsell, & N. Entwistle (Eds.), *The experience of learning: Implications for teaching and studying in higher education* (2nd ed., pp. 3-22). Edinburgh, UK: Scottish Academic Press.

Ericsson, K. A. (1996). The acquisition of expert performance. In K. A. Ericsson (Ed.), *The road to excellence: The acquisition of expert performance in the arts, sciences, sports, and games* (pp. 1-50). Mahway, NJ: Erlbaum.

Ericsson, K. A., Krampe, R. T., & Tesch-Römer, C. (1993). The role of deliberate practice in the acquisition of expert performance. *Psychological review, 100*(3), 363.

Etkina, E. (2005). Physics teacher preparation: Dreams and reality. *Journal of Physics Teacher Education Online, 3*(2), 3-9.

Fairweather, J. S. (1996). *Faculty work and public trust: Restoring the value of teaching and public service in American academic life*. Boston, MA: Allyn and Bacon.

Fairweather, J. S. (2005). Beyond the rhetoric: Trends in the relative value of teaching and research in faculty salaries. *Journal of Higher Education, 76*(4), 401-422.

Fairweather, J. S. (2008). *Linking evidence and promising practices in science, technology, engineering, and mathematics (STEM) undergraduate education*. Retrieved from Washington, DC: http://www7.nationalacademies.org/bose/PP_Commissioned_Papers.html

Fedock, P. M., Zambo, R., & Cobern, W. (1996). The professional development of college science professors as science teacher educators. *Science Education, 80*(1), 5-19.

Fisher, D. L., & Waldrip, B. G. (1999). Cultural factors of science classroom learning environments, teacher-student interactions and student outcomes. *Research in Science & Technological Education, 17*(1), 83-96.

Fraser, B. J. (1994). Research on classroom and school climate. In D. Gabel (Ed.), *Handbook of research on science teaching and learning* (pp. 493-541). New York, NY: Macmillan.

Fraser, B. J. (1998). The birth of a new journal: Editor's introduction. *Learning Environments Research, 1*(1), 1-5.

Fullan, M. (1999). *Change forces: The sequel*. Philadelphia, PA: Falmer Press.

Fullan, M. (2007). *The new meaning of educational change* (4th ed.). New York, NY: Teachers College Press.

Gallimore, R. (1996). Classrooms are just another cultural activity. In D. L. Speece & B. K. Keogh (Eds.), *Research on classroom ecologies: Implications for inclusion of children* *with learning disabilities* (pp. 229-250). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Gallos, M. R., Berg, E. v. d., & Treagust, D. F. (2005). The effect of integrated course and faculty development: Experiences of a university chemistry department in the Philippines. *International Journal of Science Education, 27*(8), 985-1006.

Garet, M. S., Porter, A. C., Desimone, L. M., Birman, B. F., & Yoon, K. S. (2001). What makes professional development effective? Results from a national sample of teachers. *American Educational Research Journal*, *38*(4), 915-945.

Geoghegan, W. (1994). Stuck at the barricades: Can information technology really enter the mainstream of teaching and learning. *AAHE bulletin*, *47*(1), 13-16.

Gibbs, G., & Coffey, M. (2004). The impact of training of university teachers on their teaching skills, their approach to teaching and the approach to learning of their students. *Active Learning in Higher Education, 5*(1), 87-100.

Glenn, J. (2000). Before it's too late: A report to the nation from the National Commission on Mathematics and Science Teaching for the 21st Century. *Washington, DC: US Department of Education*.

Goldsmith, L. T., Doerr, H. M., & Lewis, C. C. (2014). Mathematics teachers' learning: A conceptual framework and synthesis of research. *Journal of Mathematics Teacher Education*, *17*(1), 5-36.

Gow, L., & Kember, D. (1993). Conceptions of teaching and their relationship to student learning. *British Journal of Educational Psychology, 63*(1), 20-23.

Graneheim, U. H., & Lundman, B. (2004). Qualitative content analysis in nursing research: Concepts, procedures, and measures to achieve trustworthiness. *Nurse Education Today, 24*, 105-112.

Gregoire, M. (2003). Is it a challenge or a threat? A dual-process model of teachers' cognition and appraisal processes during conceptual change. *Educational Psychology Review, 15*(2), 148-179.

Gunstone, R. F., & Northfield, J. R. (1986). *Learners - teachers - researchers: Consistency in implementing conceptual change*. Paper presented at the American Educational Research Association, San Francisco.

Gupta, A., Hammer, D., & Redish, E. F. (2010). The case for dynamic models of learners' ontologies in physics. *Journal of the Learning Sciences, 19*(3), 285-321.

Guskey, T. R. (1986). Staff development and the process of teacher change. *Educational Researcher, 15*(5), 5-12.

Guskey, T. R. (2002). Professional development and teacher change. *Teachers and Teaching: Theory and Practice, 8*, 381-391.

Guskey, T. R., & Huberman, M. (1995). *Professional development in education: New paradigms and practices*. New York, NY: Teachers College Press.

Guzzetti, B. J., Snyder, T. E., Glass, G. V., & Gamas, W. S. (1993). Promoting conceptual change in science: A comparative meta-analysis of instructional interventions from reading education and science education. *Reading Research Quarterly*, *28*(2), 116-159.

Hake, R. R. (1998). Interactive engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American Journal of Physics, 66*(1), 64-74.

Hall, G. E., George, A. A., & Rutherford, W. L. (1998). *Measuring stages of concern about the innovation: A manual for the use of the stages of concern questionnaire*. Austin, TX: Southwest Educational Development Laboratory.

Halloun, I. A., & Hestenes, D. (1985). The initial knowledge state of college physics students. *American Journal of Physics, 53*, 1043-1055.

Hammer, D. (1996). Misconceptions or p-prims: How may alternative perspectives of cognitive structure influence instructional perceptions and intentions? *The Journal of the Learning Scienes, 5*(2), 97-127.

Handelsman, J., Ebert-May, D., Beichner, R. J., Bruns, P., Chang, A., DeHaan, R., . . . Wood, W. B. (2004). Scientific teaching. *Science, 304*(5670), 521-522.

Harris, L. R. (2011). Phenomenographic perspectives on the structure of conceptions: The origins, purposes, strengths, and limitations of the what/how and referential/structural frameworks. *Educational Research Review, 6*, 109-124.

Hasselgren, B., & Beach, D. (1997). Phenomenography - a "good-for-nothing brother" of phenomenlogy? Outline of an analysis. *Higher Education Research and Development, 16*(2), 191-202.

Hatch, J. A. (2002). *Doing qualitative research in education settings*. Albany, NY: State University of New York Press.

Henderson, C. (2012, May). *Evaluation of the physics and astronomy new faculty workship.* Paper presented at the The Role of Scientific Societies in STEM Faculty Workships, Washington, DC.

Henderson, C., Beach, A., & Famiano, M. (2009). Promoting instructional change via co-teaching. *American Journal of Physics, 77*, 274-283.

Henderson, C., Beach, A., & Finkelstein, N. (2011). Facilitating change in undergraduate STEM instructional practices: An analytic review of the literature. *Journal of Research in Science Teaching, 48*(8), 952-984.

Henderson, C., Beach, A., Finkelstein, N., Larson, R. S., Henderson, C., Sabella, M., & Hsu, L. (2008). *Facilitating change in undergraduate STEM: Initial results from an interdisciplinary literature review.* Paper presented at the AIP Conference Proceedings-American Institute of Physics.

Henderson, C., & Dancy, M. H. (2007). Barriers to the use of research-based instructional strategies: The influence of both individual and situational characteristics. *Physical Review Special Topics - Physics Education Research, 3*(2), 1-14.

Henderson, C., & Dancy, M. H. (2008). Physics faculty and educational researchers: Divergent expectations as barriers to the diffusion of innovations. *American Journal of Physics, 76*(1), 79-91.

Henderson, C., Dancy, M. H., & Niewiadomska-Bugaj, M. (2012). Use of research-based instructional strategies in introductory physics: Where do faculty leave the innovation-decision process? *Physical Review Special Topics - Physics Education Research, 8*, 1-15.

Hesse, J. (1989). From naive to knowledgeable. *The Science Teacher, 56*(6), 55-58.

Hestenes, D., & Jackson, J. (1996). *Partnerships for physics teaching reform - a crucial role for universities and colleges*. Paper presented at the International Conference on Undergraduate Physics, College Park, MD.

Hestenes, D., Wells, M., & Swackhamer, G. (1992). Force concept inventory. *The Physics Teacher, 30*(3), 141-151.

Hewson, P. W. (1981). A conceptual change approach to learning science. *European Journal of Science Education, 3*, 383-396.

Hewson, P. W. (1992). *Conceptual change in science teaching and teacher education*. Paper presented at the Research and Curriculum Development in Science Teaching, Madrid, Spain. http://annenbergmedia.org/workshops/lala2/support/hewson.pdf

Hewson, P. W., Beeth, M. E., & Thorley, N. R. (1998). Teaching for conceptual change. In B. J. Fraser & K. G. Tobin (Eds.), *International Handbook of Science Education* (pp. 199-218). Dordrecht, Netherlands: Kluwer.

Hewson, P. W., & Hewson, M. G. (1988). An appropriate conception of teaching science: A view from studies of science learning. *Science Education, 72*(5), 597-614.

Hewson, P. W., Tabachnick, B. R., Zeichner, K. M., Blomker, K. B., Meyer, H., Lemberger, J., . . . Toolin, R. (1999). Educating prospective teachers of Biology: Introduction and research methods. *Science Education, 83*(3), 373-384.

Hilborn, R. C. (1997). Guest comment: Revitalizing undergratue physics - who needs it? *American Journal of Physics, 65*, 175-177.

Hilborn, R. C., Howes, R. H., & Krane, K. S. (2003). *Strategic programs for innovations in undergraduate physics: Project report* Retrieved from College Park, MD:

Ho, A., Watkins, D., & Kelly, M. (2001). The conceptual change approach to improving teaching and learning: An evaluation of a Hong Kong staff development programme. *Higher Education, 42*(2), 143-169.

Hodapp, T. (2011). The economics of education: Closing undegraduate physics programs. *APS News, 20*(11), 8.

Hoepfl, M. (1997). Choosing qualitative research: A primer for technology education researchers. *Journal of Technology Education*, *9*(1), 47-63. Retrieved from http://scholar.lib.vt.edu/ejournals/JTE/v9n1/hoepfl.html

Hoffer, T. (1995). High school curriculum differentiation and postsecondary outcomes. In P. W. Cookson & B. Schneider (Eds.), *Transforming schools* (pp. 371-402). New York, NY: Garland.

Holmqvist, M. (2011). Teachers' learning in a learning study. *Instructional Science*, *2011*(39), 497-511.

Holmqvist, M., Gustavsson, L., & Wernberg, A. (2008). Variation theory - an organizing principle to guide design research in education. In A. E. Kelly, R. A. Lesh, & J. Y. Baek (Eds.), *Handbook of design research methods in education - innovations in science, technology, engineering and mathematics learning and teaching* (pp. 111-130). New York City, NY: Routledge.

Hord, S., Rutherford, W., Huling-Austin, L., & Hall, G. (1987). *Taking charge of change*. Alexandria, VA: Association for Supervision and Curriculum Development.

Huberman, M. (1992). Teacher development and instructional mastery. In A. Hargreaves & M. Fullan (Eds.), *Understanding teacher development* (pp. 193-224). New York, NY: Teachers College Press.

Huffman, D., & Heller, P. (1995). What does the force concept inventory actually measure? *The Physics Teacher*, *33*, 138-143.

Jacobs, C. (2007). Towards a critical understanding of the teaching of discipline-specific academic literacies: Making the tacit explicit. *Journal of Education*, *41*, 59-82.

Jones, S. (2008). *PRISM impact report - October 2008*. Retrieved from http://www.gaprism.org/presentations/reports/2008/impact_report1008.pdf

Justi, R., & van Driel, J. H. (2006). The use of the interconnected model of teaching professional growth for understanding hte development of science teachers' knowledge of models and modelling. *Teaching and Teacher Education, 22*, 437-450.

Kagan, D. M. (1992). Professional growth among preservice and beginning teachers. *Review of Educational Research, 62*(2), 129-169.

Kane, R., Sandretto, S., & Heath, C. (2002). Telling half the story: A critical review of research on the teaching beliefs and practices of university academics. *Review of Educational Research, 72*(2), 177-228.

Kaplan, L., & Edelfelt, R. A. (1996). Teachers for the new millennium *What Matters Most: Teaching for America's Future*: Corwin Press, Inc. National Commission on Teaching and America's Future.

Keller, G. (2001). The new demographics of higher education. *The Review of Higher Education, 24*(3), 219-235.

Kember, D. (1997). A reconceptualization of the research into university academics' conception of teaching. *Learning and Instruction, 7*(3), 255-275.

Kember, D. (2009). Promoting student-centered forms of learning across an entire university. *Higher Education, 58*, 1-18.

Kember, D., & Kwan, K.-p. (2000). Lecturers' approaches to teaching and their relationship to conceptions of good teaching. *Instructional Science, 28*, 469-490.

Kember, D., & Kwan, K.-P. (2002). Lecturers' approaches to teaching and their relationship to conceptions of good teaching. In N. Hativa & P. Goodyear (Eds.), *Teacher thinking, beliefs and knowledge in higher education* (pp. 219-239). Dordrecht: Kluwer.

Kennedy, M. M. (1998). *Form and substance in inservice teacher education.* Retrieved from Madison, WI: http://files.eric.ed.gov/fulltext/ED472719.pdf

Kluth, P., & Straut, D. (2003). Do as we say and as we do: Teaching and modeling collaborative practice in the university classroom. *Journal of Teacher Education, 54*, 228-240.

Knight, R. D. (2004). *Five easy lessons: Strategies for successful physics teaching*. San Francisco, CA: Addison Wesley.

Knight, R. D., & Andrews, J. H. (2007). *College physics a strategic approach: Student workbook* (Vol. 1). San Francisco, CA: Pearson Addison-Wesley.

Krockover, G. H., Shepardson, D. P., Adams, P. E., Eichinger, D., & Nakhleh, M. (2002). Reforming and assessing undergraduate science instruction using collaborative action-based research teams. *School Science and Mathematics, 102*(6), 266-284.

Kuhn, T. S. (1970). *The structure of scientific revolutions* (2nd ed.). Chicago, IL: University of Chicago Press.

Lam, H. C., & Tsui, B. M. A. (2013). Drawing on the variation theory to enhance students' learning of Chinese characters. *Instructional Science, 41*(5), 1-20.

Lammers, L. J., & Murphy, J. J. (2002). A profile of teaching techniques used in the university classroom. *Active Learning in Higher Education, 3*(1), 54-67.

Lawson, A., Benford, R., Bloom, I., Carlson, M., Falconer, K., Hestenes, D., . . . Wyckoff, S. (2002). Evaluating college science and mathematics instruction: A reform effort that improves teachng skills. *Journal of College Science Teaching, 31*(6), 388-393.

Lederach, J. P. (1995). *Preparing for peace: Conflict tranformation across cultures*. Syracuse, NY: Syracuse University Press.

Lee, A. M. (1970). On context and relevance. In G. Jacobs (Ed.), *The participant observer* (pp. 3-16). New York, NY: George Braziller.

Leslie, D. W. (2002). Resolving the dispute: Teaching is academe's core value. *The Journal of Higher Education, 73*(1), 49-73.

Levine, A. E. (2000). The future of colleges: 9 inevitable changes. *Chronicle of Higher Education, 47*(9), B10-B11.

Levinson-Rose, J., & Menges, R. J. (1981). Improving college teaching: A critical review of research. *Review of Educational Research, 51*(3), 403-434.

Lewin, K. (Ed.) (1951). *Field theory in social science*. New York, NY: Harper & Brothers.

Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic inquiry*. Beverly Hills, CA: Sage.

Ling, L. M., Chik, P., & Pang, M. F. (2006). Patterns of variation in teaching the colour of light to Primary 3 students. *Instructional Science, 34*(1), 1-19.

Little, J. W. (1987). Teachers as colleagues. In V. Richardson-Koehler (Ed.), *Educators' handbook: A research perspective* (pp. 491-518). New York City, NY: Longman.

Little, J. W. (1993). Teachers' professional development in a climate of educational reform. *Educational Evaluation and Policy Analysis, 15*(2), 129-151.

Lortie, D. (1975). *Schoolteacher: A sociological study*. Chicago, IL: The University of Chicago Press.

Loucks-Horsley, S., Hewson, P. W., Love, N. B., & Stiles, K. (1998). *Designing professional development for teachers of science and mathematics*. Thousand Oaks, CA: Corwin Press.

Loucks-Horsley, S., & Matsumoto, C. (1999). Research on professional development for teachers of mathematics and science: The state of the scene. *School Science and Mathematics, 99*(5), 258-270.

Loucks-Horsley, S., Stiles, K., & Hewson, P. W. (1996). *Principles of effective professional development for mathematics and science education: A synthesis of standards*. Retrieved from Madison, WI: http://files.eric.ed.gov/fulltext/ED409201.pdf

MacIsaac, D., & Falconer, K. (2002). Reforming physics instruction via RTOP. *The Physics Teacher, 40*, 479-485.

Magnusson, S., Krajcik, J., & Borko, H. (1999). Nature, sources, and development of pedagogical content knowledge for science teaching. In J. Gess-Newsome & N. G. Lederman (Eds.), *Examining pedagogical content knowledge: The construct and its implications for science education* (pp. 95-132). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Marshall, D., Conana, H., Maclon, R., Herbert, M., & Volkwyn, T. (2011). Learning as accessing a disciplinary discourse: Integrating academic literacy into introductory physics thorugh collaborative partnerships. *Across the Disciplines, 8*(3). Retrieved from http://wac.colostate.edu/atd/clil/marshalletal.cfm

Martin, E., & Balla, M. (1991). Conceptions of teaching and implications for learning. In B. Ross (Ed.), *Teaching for effective learning: Research and development in higher education* (Vol. 13, pp. 298-304). Sydney, Australia: Higher Education Research and Development Society of Australasia, Problem-based Learning Assessment and Research Centre.

Martin, E., Trigwell, K., Prosser, M., & Ramsden, P. (2003). Variation in the experience of leadership of teaching in higher education. *Studies in Higher Education*, *28*(3), 247-259.

Marton, F. (1981). Phenomenography - Describing conceptions of the world around us. *Instructional Science*, *10*, 177-200.

Marton, F. (1986). Phenomenography: A research approach to investigating different understanding of reality. *Journal of Thought*, *21*, 28-49.

Marton, F. (1994). Phenomenography. In T. Husen & T. N. Postlethwaite (Eds.), *The international encyclopedia of education* (2nd ed., Vol. 8, pp. 4424-4429). Oxford, UK: Pergamon.

Marton, F., & Booth, S. (1997). *Learning and awareness*. Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Marton, F., & Saljo, R. (1997). Approaches to learning. In F. Marton, D. Hounsell, & N. Entwistle (Eds.), *The experience of learning: Implications for teaching and studying in higher education* (2nd ed., pp. 39-58). Edinburgh, UK: Scottish Academic Press.

Marton, F., & Tsui, B. M. A. (2004). *Classroom discourse and the space of learning*. Mahwah, NJ: Lawrence Erlbaum.

Maskiewicz, A. C., & Lineback, J. E. (2013). Misconceptions are "so yesterday!". *CBE-Life Sciences Education*, *12*(3), 352-356.

Massod, S. S. (2007). *Better physics teaching can increase physics enrollment*. Retrieved from Houston, TX: http://arxiv.org/pdf/physics/0702089.pdf

Massy, W. F., Wilger, A. K., & Colbeck, C. (1994). Departmental cultures and teaching quality: Overcoming "hollowed" collegiality. *Change: The Magazine of Higher Learning, 26*(4), 11-20.

Mattessich, P. W., & Monsey, B. R. (1992). *Collaboration: What makes it work. A review of research literature on factors influencing successful collaboration.* St. Paul, MN: Amherst H. Wilder Foundation.

McCloskey, M. (1983). Intuitive physics. *Scientific American, 248*(4), 122-130.

McDermott, L. C. (1991). Millikan Lecture 1990: What we teach and what is learned - Closing the gap. *American Journal of Physics, 59*(4), 301-315.

McDermott, L. C. (1993). Guest Comment: How we teach and how students learn - A mismatch? *American Journal of Physics, 61*(4), 295-298.

McDermott, L. C. (2006). Preparing K-12 teachers in physics: Insights from history, experience, and research. *American Journal of Physics, 74*, 758-762.

McDermott, L. C., Heron, P. R. L., & Shaffer, P. S. (2005). Preparing K-12 teachers to teach physics and physical science. *APS Forum on Education Newsletter*(Summer 2005), 19-22.

McDermott, L. C., Schaffer, P. S., & Somers, M. D. (1993). Research as a guide for teaching introductory mechanics: An illustration in the context of the Atwood's machine. *American Journal of Physics, 62*(1), 46-54.

McDuffie, A. R., & Graeber, A. (2003). Institutional norms and policies that influence college mathematics professors in the process of changing to reform-based practices. *School Science and Mathematics, 103*(7), 331-344.

McKenzie, J. A. (2003). *Variation and change in university teachers' ways of experiencing teaching.* (Doctoral dissertation), University of Technology, Sydney. Retrieved from https://opus.lib.uts.edu.au

McLoughlin, A. S., & Dana, T. M. (1999). Making science relevant: The experiences of prospective elementary school teachers in an innovatie science content course. *Journal of Science Teacher Education, 10*(2), 69-91.

Merriam, S. B. (1998). *Qualitative research and case study application in education.* San Francisco, CA: Jossey-Bass.

Merton, P., Clark, C., Richardson, J., & Froyd, J. (2001). *Engineering curiculla change across the foundation coalition: How they succeeded, what they learned.* Paper presented at the Proceedings of the ASEE Annual Conference.

Mestre, J. P. (2001). Implications of research on learning for the education of prospective science and physics teacher. *Physics Education,* 44-51.

Mewborn, D. S., Beckmann, S., Davion, V., Desmet, C., Hudson-Ross, S., Oliver, J. P., . . . Ruppersburg, H. (2002). Expanding the "great conversation" to include arts & sciences faculty. *Innovative Higher Education, 27*(1), 39-51.

Murawski, W. W., & Swanson, H. L. (2001). A meta-analysis of co-teaching research. *Remedial and Special Education, 22*(5), 258-267.

Norton, L., Richardson, J. T. E., Hartley, J., Newstead, S., & Mayes, J. (2005). Teachers' beliefs and intentions concerning teaching in higher education. *Higher Education, 50*, 537-571.

NRC. (1995). *National science education standards*. Washington, DC: National Acadamies Press.

NRC. (1996). *National science education standards*. Washington, DC: National Academy Press.

NRC. (2012a). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: The National Academies Press.

NRC. (2012b). *An interim report on assuring DOD a strong science, technology, engineering, and mathematics (STEM) workforce*. Washington, DC Retrieved from http://www.nap.edu/catalog.php?record_id=13433.

NSF. (1996). *Shaping the future: New expectations for undergraduate education in science, mathematics, engineering, and technology*. Retrieved from Arlington, VA: http://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf96139

O'Meara, K., & Braskamp, L. (2005). Aligning faculty reward systems and development to promote faculty and student growth. *NASPA Journal, 42*(2), 223-240.

Oppenheimer, R. (1954, 27 December). *The New York Times*.

Otero, V. K. (2005). *Recruiting talented mathematics and science majors to careers in teaching: A collaborative effort for K-16 educational reform*. Paper presented at the 2005 Annual Meeting of the American Association for the Advancement of Science, Washington, DC.

Pajares, M. F. (1992). Teachers' beliefs and educational research: Cleaning up a messy construct. *Review of Educational Research, 62*(3), 307-332.

Palmer, D. (2008). Practices and innovations in Australian science teacher education programs. *Research in Science Education, 38*, 167-188.

Palmer, P. J. (1993). *To know as we are known: A spirituality of education*. San Francisco, CA: HarperSanFrancisco.

Pang, M. F. (2003). Two faces of variation: On continuity in the phenomenographic movement. *Scandinavian Journal of Educational Research, 47*(2), 145-156.

Park, S., & Chen, Y.-C. (2012). Mapping out the integration of the components of pedagogial content knowledge (PCK): Examples from high school biology classrooms. *Journal of Research in Science Teaching, 49*(7), 922-941.

Patton, M. Q. (1990). *Qualitative evaluation and research methods* (Vol. 2nd). Newbury Park, CA: Sage Publications, Inc.

PCAST. (2012). *Engage to Excel: Producing One Million Additional College Graduates with Degrees in Science, Technology, Engineering, and Mathematics. Report to the President*. Retrieved from Washington, DC: http://files.eric.ed.gov/fulltext/ED541511.pdf

Peterman, F. P. (1993). Staff development and the process of changing: A teacher's emerging constructivist beliefs about learning and teaching. In K. Tobin (Ed.), The practice of constructivism in science education (pp. 227-245). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

PhysTEC. (2013). Physics Teacher Education Coalition. Retrieved from http://www.phystec.org/components/collaboration/index.php

Piburn, M. D., Sawada, D., Turley, J., Falconer, K., Benford, R., Bloom, I., & Judson, E. (2000). *Reformed teaching observation protocol (RTOP): Reference manual*. Retrieved from Tempe, AZ:

Pintrich, P. R., Marx, R. W., & Boyle, R. A. (1993). Beyond cold conceptual change: The role of motivational beliefs and classroom contextual factors in the process of conceptual change. *Review of Educational Research, 63*(2), 167-199.

Ponterotto, J. G. (2006). Brief note on the origins, evolution, and meaning of the qualitative research concept "thick description". *The Qualitative Report, 11*(3), 538-549.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*(2), 211-227.

Postareff, L., Lindblom-Ylanne, S., & Nevgi, A. (2007). The effect of pedagogical training on teaching in higher education. *Teaching and Teacher Education*, *23*, 557-571.

Postareff, L., Lindblom-Ylanne, S., & Nevgi, A. (2008). A follow-up study of the effect of pedagogical training on teaching in higher education. *Higher Education, 56*, 29-43.

Powell, K. (2003). Science education: Spare me the lecture. *Nature, 425*(6955), 234-236.

Pratt, D. D. (1992). Conceptions of teaching. *Adult Education Quarterly, 42*(4), 203-220.

Pride, T. O. B., Vokos, S., & McDermott, L. C. (1998). The challenge of matching learning assessments to teaching goals: An example from the work-energy and impulse-momentum theorems. *American Journal of Physics*, *66*(2), 147-157.

Prince, M., Borrego, M., Henderson, C., Cutler, S., & Froyd, J. (2013). Use of research-based instructional strategies in core chemical engineering courses. *Chemical Engineering Education, 47*(1), 27-37.

Prosser, M., & Trigwell, K. (1999). *Understanding learning and teaching: The experience in higher education*. Buckingham, England: Open University Press.

Prosser, M., Trigwell, K., & Taylor, P. (1994). A phenomenographic study of academics' conceptions of science learning and teaching. *Learning and Instruction*, *4*, 217-231.

Pundak, D., Rozner, S., Yacobson, F., & Toledano-Kitay, D. (2008). How to adopt active learning. *Al Hagova–Journal on Teaching in Higher Education*, *7*, 18-21.

Putnam, R. T., & Borko, H. (2000). What do new views of knowledge and thinking have to say about research on teacher learning? *Educational Researcher*, *29*(1), 4-15.

Quinlan, K. M. (1999). Commonalities and controversy in context: A study of academic historians' educational beliefs. *Teaching and Teacher Education, 15*, 447-463.

Ramsden, P., Prosser, M., Trigwell, K., & Martin, E. (2007). University teachers' experiences of academic leadership and their approaches to teaching. *Learning and Instruction, 17*, 140-155.

Redish, E. F. (2003). *Teaching physics with the physics suite*. Hoboken, NJ: John Wiley & Sons, Inc.

Redish, E. F., & Steinberg, R. N. (1999). Teaching physics: Figuring out what works. *Physics Today, 52*(1), 24-30.

Rhoton, J., & McLean, J. E. (2008). Developing teacher leaders in science: Catalysts for improved science teaching and student learning. *Science Educator, 17*(2).

Richardson, J. T. E. (1999). The concepts and methods of phenomenographic research. *Review of Educational Research, 69*(1), 53-82.

Richardson, L. (2000). Writing: a method of inquiry. In N. K. Denzin & Y. S. Lincoln (Eds.), *Handbook of qualitative research* (2nd ed., pp. 923-943). Thousand Oaks, CA: Sage.

Richardson, V. (1990). Significant and worthwhile change in teaching practice. *Educational Researcher, 19*(7), 10-18.

Roth, W.-M., & Tobin, K. (2001). Learning to teach science as practice. *Teaching and Teacher Education, 17*, 741-762.

Roth, W.-M., & Tobin, K. (2002). College physics teaching: From boundary work to border crossing and community building. In P. C. Taylor, P. J. Gilmore, & K. Tobin (Eds.), *Transforming undergraduate science teaching: Social constructivist perspectives* (pp. 146-180). New York, NY: Peter Lang Publishing, Inc.

Roth, W.-M., & Tobin, K. (2004). Coteaching: from praxis to theory. *Teachers and teaching, 10*(2), 161-179. Retrieved from http://sfx.galib.uga.edu/sfx_gsu1?sid=google&auinit=WM&aulast=Roth%2A&atitle=Coteaching%3A%20From%20praxis%20to%20theory&id=doi%3A10.1080%2F0954025032000188017

Rubin, H. J., & Rubin, I. S. (2005). *Qualitative interviewing: The art of hearing data* (2nd ed.). Thousand Oaks, CA: Sage Publications, Inc.

Runesson, U. (2006). What is it possible to learn? On variation as a necessary condition for learning. *Scandinavian Journal of Educational Research, 50*(4), 397-410.

Rutz, C., Condon, W., Iverson, E. R., Manduca, C. A., & Willett, G. (2013). Faculty professional development and student learning: What is the relationship? *Change, 44*(3), 40-46.

Samuelowicz, K., & Bain, J. D. (1992). Conceptions of teaching held by academic teachers. *Higher Education, 24*(1), 93-111.

Samuelowicz, K., & Bain, J. D. (2001). Revisiting academics' beliefs about teaching and learning. *Higher Education, 41*, 299-325.

Sanders, T. (2004). *No time to waste: The vital role of college and university leaders in improving science and mathematics education.* Paper presented at the Invitational Conference on Teacher Preparation and Institutions of Higher Education, U. S. Department of Education, Washington, DC.

Saul, J. M. (2002). *Unit IV: Worksheet 1* (2.0 ed.). Albuquerque, NM: University of New Mexico.

Sawada, D., Piburn, M. D., Judson, E., Turley, J., Falconer, K., Benford, R., & Bloom, I. (2002). Measuring reform practices in science and mathematics classrooms: The reformed teaching observation protocol. *School Science and Mathematics, 102*(6), 245-253.

Schein, E. H. (1999). Kurt Lewin's change theory in the field and in the classroom: Notes towar a model of managed learning. *Reflections*, *1*(1), 59-74.

Schommer, M. (1994). Synthesizing epistemological belief research: Tentative understandings and provocative confusions. *Educational Psychology Review*, *6*(4), 293-319.

Schon, D. A. (1995). The new scholarship requires a new epistemology. *Change, 27*(6).

Schraw, G., Crippen, K. J., & Hartley, K. (2006). Promoting self-regulation in science education: Metacognition as part of a broader perspective on learning. *Research in Science Education, 36*, 111-139.

Schuman, D. (1982). *Policy analysis, education, and everyday life*. Lexington, MA: Heath.

Scott, P. H., Asoko, H. M., & Driver, R. H. (1992). Teaching for conceptual change: A review of strategies. In R. Duit, F. Goldberg, & H. Niedderer (Eds.), *Research in physics learning: Theoretical issues and empirical studies* (pp. 310-329). Kiel, Germany: IPN.

Scruggs, T. E., Mastropieri, M. A., & McDuffie, K. A. (2007). Co-teaching in inclusive classrooms: A metasynthesis of qualitative research. *Exceptional Children, 73*(4), 392-416.

Seidman, I. (1998). *Interviewing as qualitative research: A guide for researchers in education and the social sciences.* (2nd ed.). New York, NY: Teachers College Press.

Seymour, E., DeWelde, K., & Fry, C. (2011). Determining progress in improving undergraduate STEM education: The reformers' tale. A White Paper commissioned for the National Academy of Engineering Forum,"Characterizing the Impact and Diffusion of Engineering Education Innovations". Washington, DC: National Academy of Engineering.

Shulman, L. S. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review, 57*(1), 1-22.

Sin, S. (2010). Considerations of quality in phenomenographic research. *International Journal of Qualitative Methods, 9*(4), 305-319.

Sinatra, G. M. (2005). The "warming trend" in conceptual change research: The legacy of Paul R. Pintrich. *Educational Psychologist, 40*(2), 107-115.

Singer, S. R., Nielsen, N. R., & Schweingruber, H. A. (2012). *Discipline-based education research: Understanding and improving learning in undergraduate science and engineering*: National Academies Press.

Singer, S. R., & Smith, K. A. (2013). Discipline‐based education research: Understanding and improving learning in undergraduate science and engineering. *Journal of Engineering Education, 102*(4), 468-471.

Slotta, J. D., & Chi, M. (2006). Helping students understand challenging topics in science through ontology training. *Cognition and Instruction, 24*(2), 261-289.

Smith, J., diSessa, A. A., & Roschelle, J. (1993). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *The Journal of the Learning Scienes, 3*(2), 115-163.

Smith, T. M., Desimone, L. M., Zeidner, T. L., Dunn, A. C., Bhatt, M., & Rumyantseva, N. L. (2007). Inquiry-oriented instruction in science: Who teaches that way? *Educational Evaluation and Policy Analysis, 29*(3), 169-199.

Spall, S. (1998). Peer debriefing in qualitative research: Emerging operational models. *Qualitative Inquiry, 4*(2), 280-292.

Stacey, R. D. (1995). The science of complexity: An alternative perspective for strategic change processes. *Strategic Management Journal, 16*(6), 477-495.

Stacey, R. D. (1996). *Complexity and creativity in organizations*. San Francisco, CA: Berrett-Koehler Publishers, Inc.

Stake, R. E. (2000). Case Studies. In N. K. Denzin & Y. S. Lincoln (Eds.), *Handbook of qualitative research* (2nd ed., pp. 435-454). Thousand Oaks, CA: Sage Publications, Inc.

Stein, F. (2001). Re-preparing the secondary physics teacher. *Physics Education, 36*, 52-57.

Stigler, J. W., & Hiebert, J. (1999). *The teaching gap: Best ideas from the world's teachers for improving education in the classroom*. New York, NY: The Free Press.

Stoll, W., Criswell, B., & Demir, K. (2014). *Conceptual change in science teacher preparation: Collaboration between scientist and educator.* Paper presented at the NARST Annual International Conference, Pittsburgh, PA.

Stoll, W., Demir, K., & Criswell, B. (2012). *Promoting conceptual change through course design: Supporting the physics CK and PCK development of pre-service teachers*. Paper presented at the NSEUS National Conference on Research Based Undergraduate Science Teaching Conference II, Tuscaloosa, AL.

Strauss, A., & Corbin, J. (1990). *Basics of qualitative research: Grounded theory procedures and techniques*. Newbury Park, CA: Sage Publications, Inc.

Strike, K. A., & Posner, G. J. (1992). A revisionist theory of conceptual change. In R. A. Duschl & R. J. Hamilton (Eds.), *Philosophy of science, cognitive psychology, and educational theory and practice* (pp. 147-176). Albany, NY: State University of New York Press.

Sunal, C. S., Sunal, D. W., Mason, C., Zollman, D. A., Sundberg, C., & Lardy, C. (2008). Background research paper No. 2: What do we know about undergraduate science course reform? Retrieved from http://nesus.org

Sunal, D. W., Hodges, J., Sunal, C. S., Whitaker, K. W., Freeman, L. M., Edwards, L., . . . Odell, M. (2001). Teaching science in higher education: Faculty professional development and barriers to change. *School Science and Mathematics, 101*(5), 246-257.

Sunal, D. W., Sunal, C. S., Turner, D., & Steele, E. (2012). *Undergraduate science course reform and course assessment*. Paper presented at the National Association for Research in Science Teaching, Indianapolis, IN.

Sunal, D. W., Wright, E. L., & Day, J. B. (Eds.). (2004). *Reform in undergraduate science teaching for the 21st century*. Greenwich, CT: Information Age Publishing Inc.

Svensson, L. (1989). The conceptualization of cases of physical motion. *European Journal of Psychology of Education, 4,* 529-545.

Svensson, L. (1997). Theoretical foundations of phenomenography. *Higher Education Research and Development, 16*(2), 159-171.

Sykes, G. (1996). Reform of and as professional development. *Phi Delta Kappan, 77,* 465-467.

Taber, K. S. (2001). Shifting sands: A case study of conceptual development as competition between alternative conceptions. *International Journal of Science Education, 23*, 731-753.

Thielens, W., Jr. (1987). *The disciplines and undergraduate lecturing*. Paper presented at the annual meeting of the American Educational Research Association, Washington, DC.

Thorley, N. R., & Woods, R. K. (1997). Case studies of students' learning as action research on conceptual change teaching. *International Journal of Science Education, 19*, 229-245.

Tobias, S. (1990). They're not dumb. They're different. *Change, 22*(4), 11-30.

TQE. Teacher quality enhancement grants.   Retrieved from http://www2.ed.gov/programs/heatqp/faq.html

Treagust, D. F., & Duit, R. (2008). Conceptual change: A discussion of theoretical, methodological and practical challenges for science education. *Cultural Studies of Science Education, 3*, 297-328.

Trigwell, K. (2012). Relations between teachers' emotions in teaching and their approaches to teaching in higher education. *Instructional Science, 40*(3), 607-621.

Trigwell, K., & Prosser, M. (1996). Changing approaches to teaching: A relational perspective. *Studies in Higher Education, 21*(3), 275-284.

Trigwell, K., Prosser, M., & Taylor, P. (1994). Qualitative differences in approaches to teaching first year university science. *Higher Education, 27*(1), 75-84.

Trigwell, K., Prosser, M., & Waterhouse, F. (1999). Relations between teachers' approaches to teaching and students' approaches to learning. *Higher Education, 37*(1), 57-70.

Trubowitz, S. (2004). On balance: The marriage of liberal arts departments and schools of education. *Educational Horizons, 82*(2), 114-117.

Tyson, L. M., Venville, G. J., Harrison, A. G., & Treagust, D. F. (1997). A multidimensional framework for interpreting conceptual change events in the classroom. *Science Education, 81*, 387-404.

Tyson, W., Lee, R., Borman, K. M., & Hanson, M. A. (2007). Science, technology, engineering, and mathematics (STEM) pathways: High school science and math coursework and postsecondary degree attainment. *Journal of Education for Students Placed at Risk, 12*(3), 243-270.

Tytler, R. (1998). The nature of students' informal science conceptions. *International Journal of Science Education, 20*, 901-927.

Ulgens, M. (1996). On the philosophical foundation of phenomenography. In G. Dall'Alba & B. Hasselgren (Eds.), *Reflections on phenomenography: Toward a methodology?* (pp. 105-130). Goteborg, Sweden: Acta Universitatis Gothoburgensis.

van den Berg, E., Locaylocay, J., & Gallos, M. (2006). A physics teacher education program in the Philippians. *APS Forum on Education Newsletter*(Spring 2006), 33-37.

van Driel, J. H., Verloop, N., & de Vos, W. (1998). Developing science teachers' pedagogical content knowledge. *Journal of Research in Science Teaching, 35*(6), 673-695.

Van Eekelen, I., Boshuizen, H., & Vermunt, J. D. (2005). Self-regulation in higher education teacher learning. *Higher Education, 50*(3), 447-471.

Van Heuvelen, A. (1991). Learning to think like a physicist: A review of research-based instructional strategies. *American Journal of Physics, 59*(10), 891-897.

Vermunt, J. D., & Endedijk, M. D. (2011). Patterns in teacher learning in different phases of the professional career. *Learning and individual differences, 21*(3), 294-302.

Vermunt, J. D., & Verloop, N. (1999). Congruence and friction between learning and teaching. *Learning and Instruction, 9*, 257-280.

Viennot, L. (2008). Learning and conceptual understanding: Beyond simplistic ideas, what have we learned? In E. Sassi & M. Vicentini (Eds.), *Physics education: Recent developments in the interaction between research and learning* (Vol. 2): ICPE.

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. *Learning and Instruction, 4*, 45-69.

Wandersee, J. H., Mintzes, J. J., & Novak, J. D. (1994). Research on alternative conceptons in science. In D. Gabel (Ed.), *Handbook of research on science teaching and learning*. New York, NY: Macmillan.

Wei, R. C., Darling-Hammond, L., Andree, A., Richardson, N., & Orphanos, S. (2009). *Professional learning in the learning profession: A status report on teacher development in the U.S. and abroad*. Retrieved from Dallas, TX:

Weick, K. E., & Quinn, R. E. (1999). Organizational change and development. *Annual Review of Psychology, 50*, 361-386.

Weimer, M., & Lenze, L. F. (1994). Instructional interventions: A review of the literature on efforts to improve instruction. In K. Feldman & M. B. Paulsen (Eds.), *Teaching and learning in the college classrooms* (pp. 653-682). Needham Heights, MA: Ginn Press.

Weiss, I. R., Pasley, J. D., Smith, P. S., Banilower, E. R., & Heck, D. J. (2003). *Looking inside the classroom: A study of K-12 mathematics and science education in the United States.* Retrieved from Chapel Hill, NC:

Wenger, E. (1998). Communities of practice: Learning as a social system. *Systems Thinker, 9*(5), 2-3. Retrieved from http://www.co-i-l.com/coil/knowledge-garden/cop/lss.shtml website:

White, S. (2011). *Physics in US high schools: Dispelling the myths*. Paper presented at the 2011 AAPT Winter Meeting, Jacksonville, FL.

Wieman, C., Perkins, K. K., & Gilbert, S. (2010). Transforming science education at large research universities: A case study in progress. *Change, 42*(2), 6-14.

Wilson, J. M. (1994). The CUPLE Physics Studio. *The Physics Teacher*, *32*, 518-523.

Wright, E. L., & Sunal, D. W. (2004). Reform in undergrade science classrooms *Reform in undergraduate science teaching for the 21st century* (pp. 33-51). Greenwich, CT: Information Age Publishing.

Yerrick, R., Parke, H., & Nugent, J. (1997). Struggling to promote deeply rooted change: The" filtering effect" of teachers' beliefs on understanding transformational views of teaching science. *Science Education, 81*(2), 137-159.

Yin, R. K. (2009). *Case study research: Design and methods* (4 ed.). Thousand Oaks, CA: Sage Publications, Inc.

Yoon, K. S., Duncan, T., Lee, S. W.-Y., Scarloss, B., & Shapley, K. L. (2007). *Reviewing the evidence on how teacher professional development affects studetn achievement*. Retrieved from Washington, DC: http://files.eric.ed.gov/fulltext/ED498548.pdf

Zeidler, D. L., Sadler, T. D., Simmons, M. L., & Howes, E. V. (2005). Beyond STS: A research-based framework for socioscientific issues education. *Science Education*(89), 357-377.

APPENDICES

APPENDIX A

FACULTY INFORMED CONSENT FORM

[redacted]

Department of [redacted]

ADULT RESEARCH SUBJECT - INFORMED CONSENT FORM

Title: *The Change Process of Collaboration Between Science and Education Faculty*

Principal Investigator: [redacted], Assistant Professor of Science Education, [redacted]

Student Investigators: [redacted]

Purpose: You are invited to participate in a research study. The purpose of the research project is to explore the effectiveness of a collaboration between faculty from two different colleges in developing and implementing strategies used in the PHYS 7[redacted] course. One physics faculty who participated in the collaboration will be recruited for this study. Participation will require approximately five hours of your time over the 2013 summer semester. The focus question guiding the project will be: How is teaching for conceptual change conceptualized and practiced by a physics faculty in teaching PHYS 7[redacted] and other courses following a collaboration with a science education faculty in developing the PHYS 7[redacted] course. This research is being conducted at the [redacted] under the direction of Dr. [redacted].

Description of Procedures: If you decide to participate, you may participate in individual interviews (up to five per semester). These interviews are expected to be 45-60 minutes long, at a time and place scheduled around your convenience, and will be conducted, audio recorded and transcribed for data analysis by the research team (either the principal investigator (PI) or the graduate research assistant - GRA). You may also be asked to complete several survey instruments (SoCQ and Teaching Strategies). You will be asked to share course artifacts such as lesson plans, research manuscripts, conference presentations, and other scholarly work associated with the planning and implementing of PHYS 7[redacted]. You will be asked to allow researchers to videotape your instruction (students will not be filmed) in PHYS

7[redacted] and other courses. Video recording and its transcription for analysis will be completed by one of the project personnel (either the principal investigator (PI) or the graduate research assistants -GRAs).

You can withdraw from participation in the data collection process at any time without any penalty. After you have completed your participation, the research team will debrief you about the data, assumptions, and research area under study and answer any questions you may have about the research.

Risks: In this study, you will not have any more risks than you would in a normal day of life.

Benefits: Participation in this study may benefit you through the opportunity to become informed about your own teaching practices. You may increase your knowledge regarding the scholarship of teaching and learning and the importance of working in partnerships with a colleague from college of education.

Voluntary Participation: Participation in research is voluntary. You do not have to be in this study. If you decide to be in the study and change your mind, you have the right to drop out at any time. Whatever you decide, you will not lose any benefits to which you are otherwise entitled at Georgia State University.

Confidentiality: The researchers will keep your indentifying information confidential. All data collected by the research personnel will be kept confidential. Digital audio files and transcriptions will be stored on the password-protected computer of Dr. [redacted], PI, in his locked office at [redacted] for three years once the study is completed. The digital audio files, videos, and transcriptions will be destroyed in August 2016. The audio will be used only to produce a transcript that will be read only by research team members for the purpose of qualitative data analysis. The transcriptions will be de-identified, each receiving an interview number. No participant's name will be used in reporting the results of the study, and any quotation included in any written document for illustrative purposes will be anonymous. To make sure that this research is being carried out in the proper way, [redacted] IRB may review study records. The principal investigator will keep consent forms with signatures separate from data. Information may also be shared with those who make sure the study is done correctly ([redacted] Institutional Review Board and the Office for Human Research Protection (OHRP)). Your name and other facts that might point to you will not appear when we present this study or publish its results. The findings will be summarized and reported in group form. You will not be identified personally.

Contact Persons: Contact Dr. [redacted] at telephone [redacted] or [redacted] if you have questions, concerns, or complaints about this study. You can also call if you think you have been harmed by the study. Call [redacted] in the [redacted] Office of Research Integrity at [redacted] or [redacted] if you want to talk to someone who is not part of the study team. You can talk about questions, concerns, or suggestions about the study. You can also call [redacted] if you have questions or concerns about your rights in this study.

Copy of Consent Form to Subject: Before you sign this form, please ask any questions on any aspect of this study that is unclear to you. You may take as much time as necessary to think it over. You will receive a copy of this consent form to keep.

SIGNATURE SECTION – Please read carefully

You are making a decision whether or not to participate in this research study. Your signature indicates that you have read the information provided above, you have had all your questions answered, and you have decided to take part in this research. .

Permission to record: Will you permit the researchers to audio record you during this research procedure?

YES ☐ NO ☐ Initial Here _________

Permission to record: Will you permit the researchers to video record you during this research procedure?

YES ☐ NO ☐ Initial Here _________

Name of Subject (please print)	Signature	Date
Name of Person Obtaining Consent	Signature	Date

APPENDIX B

MAT STUDENT INFORMED CONSENT FORM

[redacted]

Department of [redacted]

ADULT RESEARCH SUBJECT - INFORMED CONSENT FORM

Title: Assessing Conceptual Change in a Teacher Candidate Physics Course

Principal Investigators: [redacted], Ph.D. (P.I), [redacted] and [redacted] (GRAs).

Purpose: You are invited to participate in a research study. The purpose of this research study is to investigate the effectiveness of teaching and learning strategies used in the PHYS 7[redacted] course. You are invited to participate because of your enrollment in the MAT Science Program and in PHYS 7[redacted]. A total of between 20-40 participants will be recruited for this study. Participation is expected to require no more than two hours of your time over the 2013 summer semester.

Procedures: If you decide to participate, you will be asked to share course artifacts (student course assignments, online course and discussion group postings, class journals, tests, and surveys completed by you). You will be asked to allow researchers to use audiotaped classroom discussions and you may also participate in individual interviews. Individual interviews (up to two per semester) will last approximately 20-30 minutes. Interviews will be conducted by one of the project personnel (either the principal investigator (PI) or the graduate research assistants (GRAs)). The interview will be recorded with a digital audio recorder and data will be transcribed for analysis by the researchers. The interviews will take place at the beginning and end of 2013 summer semester at a time and place scheduled around students' convenience.

Risks or Discomforts: There are few risks to participation in this study, including loss of confidentiality. If participating in interviews causes you undue anxiety, you may withdraw at any time without penalty.

Benefits: There are no direct benefits to be gained from participating; however, the research findings should support improvements in helping participants understand their own growth as future science teachers. In the science education community, documenting and assessing the implementation of overall teaching and learning strategies in the PHYS 7[redacted] course may contribute to improved science teacher preparation programs locally and possibly nationally.

Compensation to You: There is no compensation for participation in the study.

Voluntary Participation and Withdrawal:

Participation in research is voluntary. You do not have to be in this study. If you decide to be in the study and change your mind, you have the right to drop out at any time. You may skip questions or stop participating at any time. Whatever you decide, your decision will not affect your grade or standing in PHYS 7[redacted].

Confidentiality: Your privacy will be protected to the extent allowed by law. All data collected by the research personnel will be kept confidential. Digital audio files and transcriptions will be stored on the password protected computer of Dr. [redacted], PI, in his locked office at [redacted] for three years once the study is completed. The digital audio files and transcriptions will be destroyed in August 2016. The audio will be used only to produce a transcript that will be read only by research team members for the purpose of qualitative data analysis. The transcriptions will be de-identified, each receiving an interview number. No participant's name will be used in reporting the results of the study, and any quotation included in any written document for illustrative purposes will be anonymous. To make sure that this research is being carried out in the proper way, [redacted] IRB may review study records.

Contact Persons: Contact Dr. [redacted] at telephone [redacted] or [redacted] if you have questions, concerns, or complaints about this study. You can also call if you think you have been harmed by the study. Call [redacted] in the [redacted] Office of Research Integrity at [redacted] or [redacted] if you want to talk to someone who is not part of the study team.

You can talk about questions, concerns, or suggestions about the study. You can also call [redacted] if you have questions or concerns about your rights in this study.

<u>Copy of Consent Form to Subject:</u> We will give you a copy of this consent form to keep

SIGNATURE SECTION – Please read carefully

You are making a decision whether or not to participate in this research study. Your signature indicates that you have read the information provided above, you have had all your questions answered, and you have decided to take part in this research. Also, please mark specifically the parts of the research study you are willing to participate in and those you are not.

Permission to record: Please also mark the box below if you permit the researchers to audio record during research procedure (class discussions and individual interviews).

YES ☐ NO ☐ Initial Here ________

☐ Please mark if you agree to participate in individual interviews

Permission to use submitted written work (e.g., assignments, papers, etc.): Please also mark the box below if you permit the researchers to use written work during this research procedure.

YES ☐ NO ☐ Initial Here ________

Participant Signature: ________________________________Date: ___________

Researcher Signature:________________________________Date: ___________

APPENDIX C

DATA SOURCES

Primary Data Sources		Description	Timeline
Interview with Physics Professor		Semi-structured, 45- 60 minutes	
	Background interview	Focused life history – formation of conceptions and practices in teaching and learning	June 10, 2013
	Teaching Reconstruction Interviews	Three interviews – focused on physics professor's conceptions and pedagogy on teaching for conceptual change specifically in PHYS 7050 and changes which occur in them over the course.	
	Planning Interview	Focus on design and plan of PHYS 7050 and changes implement due to the collaborative experience of last year.	June 12, 2013
	Instructional Interview	Focus on current execution of PHYS 7050. Observations of the class were drawn on to question the physics professor's current views on the course, and changes in his thinking, expectations, and execution of the course.	July 10, 2013
	Executional Interview	Focus on professor's view of connection between his teaching and what the students' learned, changes in his conceptions and pedagogy on teaching for conceptual change, and self-assessment of the course.	July 31, 2013
	Reflection Interview	Focus on professor's experience in collaborating and teaching the course. Highlighting the changes the professor identifies between the collaborative course and the current course, his conceptions and pedagogy on teaching for conceptual change, and his self-assessment of the course and the results of the course. Interview followed initial data analysis and was used as part of the member checking process.	October 2013
Secondary Data Sources		Description	Timeline
Classroom Observations		Audio recorded physics professor member as he instructed, taking detailed field notes utilizing RTOP instrument	
	PHYS 7050	Observed complete cycle of instruction by the physics professor during the summer semester. Focus on teaching for conceptual change. Specifically, focusing on the treatment of student's idea.	Summer 2013
	Upper-level Lab Class (PHYS 3000)	Observed two complete classes in the middle of a physics major course taught by the physics professor Focus on the similarities and difference in the professor's teaching methods for conceptual change compared to PHYS 7050.	October 2013
	PHYS 3000 Follow-up Interview	An open-ended, semi-structured, interview focused on the physics professor's teaching for conceptual	October 2013

		change in classes for physics majors. Focus was on the observed practice in PHYS 3000 and the physics professor's perspective on this.	
MAT Student Interviews		Semi-structured interviews, randomly selected consenting students (1/2) of PHYS 7050, focus on perceptions of PHYS 7050 and understanding of teaching for conceptual change, source of clarification and collaborative evidence	
	Initial Interviews	Interview selected students in the beginning weeks of class. Focus on their understanding of the course, the syllabus, the instructor's goals, and the content of the course concentrating on teaching for conceptual change	June 2013
	Follow up Interviews	Interview same selected students near the end of the class. Focus on their perception of what they learned, the changes in the class, and verification of emerged perspectives and conjectures of the physics professor in reference to the teaching and learning in the course.	Late July 2013
Course Artifacts		Various documents and work samples will be collected through the course as supportive and collaborative evidence to findings found through interviews and observations	Summer Semester
	Syllabus	Compare similarities and differences between the current course and last summer's collaborative taught course	
	Assignments	Collection of handouts and articles utilized during the course.	
	Surveys Instruments	Force Concept Inventory (FCI) pre and post test results utilized by the instructor to gauge the change in the student's conceptual knowledge.	
		Teaching Strategies Survey - pre and post survey results will gauge both the physics professor and MAT students change in understanding and use of teaching for conceptual change.	
CBAM Instrumentation			
	Stages of Concern Questionnaire (SoCQ)	Administer the CBAM SoCQ to the physics professor at the beginning and end of the course (corresponding to the planning and finishing interviews) to gauge his progression in the use of the innovation – teaching for conceptual change	Summer Semester

APPENDIX D

INTERVIEW PROTOCOLS

Sample Interview Questions – Physics Faculty Member

Interview Framework

Each type of interview used in data collection is briefly described below. Sample open-ended questions are provided for each type interview described.

Interview #1 (Background Interview)

The first open-ended, semi-structured interview is expected to last 45-60 minutes. During this time, the researcher will focus on establishing the context of the participant's experiences by asking the interviewee to share as much as he would like about himself as a teacher and a learner –including his experiences, his thinking about teaching, about being a scientist, the preparation for teaching he received, and about personal views and current practices of teaching science through conceptual change teaching methods.

General Questions:

1. How long have you been teaching?
    a. What was your first experience of teaching? How did you prepare for it?
    b. What training have you had in teaching

2. How did you learn physics?
    a. How would you describe the classroom environment you learned in?
    b. How does this influence how you teach?

3. What events led you to begin changing your teaching methods for physics?
    a. What were the major influences in this? Challenges? Rewards?
    b. What were the changes and what were the responses from students? Colleagues? Peers outside the department?

4. What are the major differences/similarities between how you teach introductory physics courses, major physics courses, and physics courses for pre-service teachers?
    a. Do you distinguish between them in your pedagogical methods?
    b. How long have you been teaching pre-service teachers (MAT students)?
        i. What are some of the different things you've encountered in teaching them compared to undergraduates (in teaching intro level courses) and major?
        ii. Describe your relationship with the College of Education in regards to these courses?

5. What were the events that began your transition into focusing on Physics Educational Research (PER)?
    a. How would you characterize this change from traditional research to physics educational research?
        i. Was it a result of cognitive dissonance (e.g., Eric Mazur)? Or a gradual change?
        ii. What have been some of the challenges in this transition? Rewards?

6. What is physics educational research to you?
    a. What does PER focus on and what are its results?

        i. What sources do you use to inform yourself on PER?
            1. What literature do you read?
    b. What has been your experience been like of incorporating PER into your teaching?
        i. How does your research and teaching coexist?

7. What have been the perceptions of you as a physics educational researcher?
    a. How did your interest in researching PER align with the prevailing environment in the:
        - Physics and Astronomy Department
        - Physics professional community
        - College of Arts and Science
        - Broader academic community
    b. Compare and contrast this with your perception as a physics teacher using reformed methods?

8. What are your current professional goals as a physicist? As a physics instructor? As a physics education researcher?
    a. How are you pursuing them?
    b. What changes would you make if not restrained by time, culture, or resources?

9. In your new position as associate chair, how do you view your role in regards to reforming undergraduate physics education?

10. Is there anything else you would like to share regarding your teaching experience or views on teaching and learning physics?

Interview #2 (Planning Interview)

This open-ended, semi-structured interview is expected to last 45-60 minutes. During this time, the researcher will focus on establishing the participants' conceptions and practices on teaching for conceptual change. The context for this will be the physics faculty's planning for PHYS 7050, his personal views and current practices of teaching science through conceptual change teaching, and how he plans to incorporate this into the course.

General Questions:

1. What is your understanding of teaching for conceptual change?
    a. In general, in what ways does your teaching reflect this view?
        i. How much of these perspectives will be incorporated into PHYS 7050?
        ii. What conceptual change strategies will you incorporate into PHYS 7050? And why?

2. How will you focus on students learning both physics content and pedagogy for teaching for conceptual change and integrating them?
    a. What evidence will you look at to measure this?

3. What did you learn from your collaboration in teaching PHYS 7050 last year?
        i. What did you learn that will be easy for you to reproduce by yourself?
        ii. What will be a challenge to do by yourself?
        iii. What did you learn that is applicable to other classes? And how much of these have you used?

4. At this point, looking back of the collaboration and co-teaching, what are some of the things that you would like to have gained more expertise in to prior to teaching PHYS 7050 independently from teaching for conceptual change perspective?
        i. Has there been anything you done since that time to broaden your understanding of conceptual change?
        ii. What has been the extent of the collaboration since the co-teaching last summer?

5. How have you planned for PHYS 7050, this summer?
    a. Changes in the structure of the course (content and pedagogy),
    b. Change in the syllabus (mentioned having a little harder syllabus in previous interview)
    c. Changes in your philosophy from last year?
    d. What are your major goals for the course?
        i. For the students?
        ii. For you as an instructor?

6. What roles will student ideas play in your teaching PHYS 7050?
    a. How will you identify them?
    b. How will you address ideas which vary from accepted physics concepts?
    c. How will you instruct the future teachers to approach student ideas?
    d. What type and how much emphasis will you devote to them?

7. How will you assess the accomplishment of the goals?
    a. How will you know if a student has learned something in PHYS 7050?
    b. How will the student know if they had learned something?

8. What are some of the major barriers in teaching PHYS 7050? (time constraints emphasized in prior interview)
    a. How are you planning to overcome them?

b. A tension you identified in a prior interview, was wanting to cover the material at the end (momentum and waves), so you switched to lecture mode in order for the students to see the material, but on the other hand you expressed doubt as to whether the students actually learned anything in this process, what is your current view on this?
    - How will you approach this tension this year?

9. Is there anything you would like to add, related to anything that we talked about today?

Interview #3 (Instructional Interview)

This open-ended, semi-structured interview is expected to last 45-60 minutes. During this time, the researcher will focus on establishing the participants' conceptions and practices on teaching for conceptual change. The context for this will be the physics faculty's current pedagogy in PHYS 7210, his personal views and current practices of teaching science through conceptual change teaching, and how he is currently incorporating them into the course. The specific focus of the interview will be the physics faculty's current teaching methods for teaching for conceptual change, the variations of practices within them, and how these methods have evolved from prior discussions and observations. General type questions are shown below. Prior to the interview these questions will be expanded and modified based on analysis of previous interviews and classroom observations.

General Questions:

1. In the context of PHYS 7050, what does teaching for conceptual change mean to you?
    a. What does this look like currently in your teaching of PHYS 7050?
    b. What specific strategies are you incorporating into PHYS 7050 to teach for conceptual change?

2. At this point in PHYS 7050, what aspects of your teaching in the course in your estimation are going better than expected? What evidence would you point to showing this?
    a. In your approach for teaching for conceptual change which strategies are being executed as planned?
    b. What strategies for teaching for conceptual change have you modified? Why?
    c. What strategies for teaching for conceptual change have not been effective?

3. How have your conceptions of teaching for conceptual change evolved from the beginning of the course?
    a. Is this currently reflected in your teaching practices? If so be specific.

4. At this point what is your assessment of the students' learning of physics content? physics pedagogy? What evidence are you basing this on? How are you currently assessing the learning?
    a. How are you focusing on students learning both physics content and pedagogy for teaching for conceptual change and integrating them?
        i. What evidence are you using to measure this?
    b. Based on your assessment of the learning, what aspects of the class are you planning on modifying? Why? What specific strategies are you planning to use in this modifying?

5. From the MAT students' perspective, what learning would they currently identify as occurring in PHYS 7050? Why? Evidence?
    a. What teaching strategies would they identify as the most effective? Why? Evidence?

6. What are some of the major barriers you've faced so far in teaching PHYS 7050?
    a. How have you overcome them? Or how are you planning on overcoming them?

7. In your estimation, how does PHYS 7050 compare to the collaborative course taught last summer at this point? What are the improvements? What aspects are being emphasized more/less this year than last?

8. At this point, looking back of the collaboration and co-teaching of last summer, what are some of the things that you would like to have gained more expertise in to prior to teaching PHYS 7050 independently?
    i. Has there been anything you done or are currently doing to broaden your understanding of conceptual change while teaching this course?
    ii. What has been the extent of any collaboration or consulting with science education faculty while teaching PHYS 7050 summer?

9. Is there anything you would like to add, related to anything that we talked about today

Interview #4 (Assessment Interview)

This open-ended, semi-structured interview is expected to last 45-60 minutes. During this time, the researcher will focus on establishing the participants' conceptions and practices on teaching for conceptual change. The context for this will be the physics faculty's assessment of his pedagogy in PHYS 7050, his personal views and reasons behind his current practices of teaching science through conceptual change teaching, and his assessment of student learning of physics content, pedagogy of teaching for conceptual change, and the integration of both from the course. General type questions are shown below. Prior to the interview these questions will be expanded and modified based on analysis of previous faculty and student interviews along with classroom observations.

General Questions:

1. In the context of PHYS 7050, what did teaching for conceptual change mean to you?
    a. What does this look like in your teaching of PHYS 7050?
    b. What specific strategies did you incorporating into PHYS 7050 to teach for conceptual change? How did those vary over the course?

2. At this point in PHYS 7050, what aspects of your teaching in the course in your estimation are going better than expected? What evidence would you point to showing this?
    a. In your approach for teaching for conceptual change which strategies are being executed as planned?
    b. What strategies for teaching for conceptual change have you modified? Why?
    c. What strategies for teaching for conceptual change have not been effective?

3. What did the students learn in the course about physics content? Evidence?
    a. Physics pedagogy for teaching for conceptual change?
    b. The integration of both?

4. From the MAT students' perspective, what learning would they have identified as occurring in PHYS 7050? Why? Evidence?
    a. What teaching strategies would they identify as the most effective? Why? Evidence?
    b. Reference specific examples given in the MAT final interviews to elicit his reaction and reasons for why this might be.
    c.
5. In your estimation, how did the (physics content, pedagogy, and integration) learning in PHYS 7050 this year compare to the collaborative course taught last summer? What are the reasons for any differences?

6. What did you learn from teaching PHYS 7050 this year?
    a. Learning of teaching for conceptual change?
        i. What changes have there been in your view of the role of students' initial ideas in

teaching and learning of physics?
   b. Learning of integration of content and pedagogy?

7. How does your learning this year compare to your learning last your through the collaboration?
   a. Learning of teaching for conceptual change?

8. In what ways did this course and the prior collaboration contribute to your perspective on physics teaching and learning?
   a. What aspects of what you learned will you incorporate in the teaching of future courses (introductory, major, and pre-service)?

9. If you were to run this course in the future, in what ways might you revise its design and implementation?
   a. What advice would you give to other people who might try to engage in conducting a collaboratively-taught course like this?

10. Is there anything you would like to add, related to anything that we talked about today?

Interview #5 (Reflection Interview)

This open-ended, semi-structured interview is expected to last 45-60 minutes. During this time, the researcher will focus on establishing the impact that collaborating and teaching PHYS 7050 had on the participant's conceptions and practices on teaching for conceptual change. The context for this will be the assessment of student learning in PHYS 7050, the physics faculty's reflection on conceptions and practices of teaching science through conceptual change teaching as exhibited in PHYS 7050, changes he identified in his conceptions and practices, and finally the future impact of these changes both on his teaching and his influence. General type questions are shown below. Prior to the interview these questions will be expanded and modified based on analysis of previous faculty and student interviews along with classroom observations.

General Questions:

1. What does teaching for conceptual change mean to you?
    a. How did your teaching strategies for teaching for conceptual change vary over the semester in PHYS 7050?
    b. What impact did this have on your ideas about teaching for conceptual change?

2. Based on your assessments of PHYS 7050, what did the students learn in the course?
    a. Physics content?
    b. Physics pedagogy for teaching for conceptual change?
    c. The integration of both?

3. How did this match up with your expectations? (reference previous statements about learning results prior to formal assessment)
    a. What aspects of the course were the most effective?
    b. What aspects of the course were most challenging?

4. In PHYS 7050 what initial planned strategies for teaching for conceptual change worked the best? Why?
    a. What strategies for teaching for conceptual change were not effective? Why?
    b. What new and/or modified strategies for teaching for conceptual change did you try over the semester?
    c. Of these strategies which one will you use in future PHYS 7050 courses? Other courses? Why?

5. In your estimation, how did the PHYS 7050 this year compare to the collaborative course taught last summer? What are the reasons for any differences?

6. Reflection back on the process of co-teaching followed by independently teaching PHYS 7050, what

has been the impact on your ideas of physics teaching, your practices of physics teaching?

   a. What major changes have you perceived?
   b. What were the key influences in these changes?

7. How will the experience affect your future teaching (introductory, major, and pre-service courses)?
   a. Your research?
   b. Your future development (PD and other collaborations)?

8. If you were to run this course in the future, in what ways might you revise its design and implementation?
   a. What advice would you give to other people who might try to engage in conducting a collaboratively-taught course like this?

9. What would be your recommendations for other physics faculty be based on this experience? Your department? Your college?

10. Is there anything you would like to add, related to anything that we talked about today?

PHYS 3000 Follow-up Interview

This open-ended, semi-structured interview is expected to last 30-45 minutes. During this time, the researcher will focus on establishing the impact that collaborating and teaching PHYS 7050 had on the participant's planning and instruction in the observed classes of PHYS 3000. The context for this will be the direct classroom observation of 3000 and the physics faculty's reflections on these and his perspective on his planning and teaching in PHYS 3000. General type questions are shown below. Prior to the interview these questions will be expanded and modified based on analysis of the direct 3000 classroom observations.

General Questions:

1. What role does teaching for conceptual change play in your planning and teaching this lesson?
   a. How did your knowledge of common misconceptions on this subject influence your instruction?

2. What influence if any did the collaboration the past two summers play in your planning and how you taught the classes?

3. What reflection and planning went on between the two classes?
   a. What were the motivations?

Specific Methodology Questions

4. You started the beginning of both classes by directly questioning of students? What was your reason for this?
   - As the class progressed, you used more passive questions like - 'Any questions?' 'Are we good there? Good so far? Questions so far? Are your brains getting tired? What were you seeking there?
   - these questions were followed with a wide variety of pauses from almost no pause to several seconds. What dictated how long you paused?
     i. In the 2nd class in particular. Several times the long pause ended with a question of clarification from a student.

Question about the difference between the two classes

5. What prompted your switching the presentations order of the labs between the classes?
   - It appeared you know better the background of where the students were coming from the second time?
     i. Did that influence how you taught it the second time? If so how?

6. In the 2nd class you asked student to predict the outcome of the compact fluorescent curve? 1st time provided the information. Why?

7. In the 2nd class you let student questions about a result take you into a tangent on color. Didn't see that first time? Was this a conscious decision and what was the reason behind it?

8. On the Michelson interferometer you presented similar information both times, but placed the emphasizes on different parts:

- 1st time spent a long time developing the historical background while eliciting students input into the general time periods involved. Emphasized the idea about the ether and how Michelson's experiments contradicted the expected results.
- -2nd time quickly recapped historical development no eliciting of student's understanding of this. Emphasized the idea of speed of wave depends on medium. Then asked question of students for light from stars what is the medium? Used this to introduce ether. Again developed the concept but did less development of scientific misconception and startling results of Michelson' experiment - immediately jumped to Einstein and his conclusion 'giving up absolute values for space and time"

Student Interview Protocol

Each type of interview used in data collection is briefly described below. Sample open-ended questions are provided for each type interview described.

Interview #1(Initial)

The researcher will conduct the first semi-structured interviews expecting to last 20-30 minutes during the beginning of the summer session. During that time, the researcher will focus on establishing the context of the participants' experiences by asking them to share as much as they would like about themselves as teachers, as physics students, and/or future physics teachers. –including their experiences (especially in learning physics), their thinking about being science teachers, and the preparation for teaching they had received prior to their enrollment into PHYS 7050.

1. What can you tell me about your educational background and work experiences, if there is any?
2. What teaching experience have you had in teaching science prior to this summer?
3. What is your ideal view of science teaching and learning?
    a. How did you arrive to this view? Or how did this evolved?
4. Describe your experience in learning physics to this point?
    a. How is this related to your ideal vision of teaching and learning of science?
    b. Is teaching and learning of physics any different than other science subjects?
5. In your opinion, what are the most important qualities that a physics teacher should have to teach physics more effectively?
    a. In your opinion, what kind of roles do teacher and students need to adopt for teaching and learning of physics?
6. What roles do students' initial ideas play in teaching and learning of physics?
    a. In what ways have you/would you incorporate/d this in teaching and learning of physics?
    b. In what ways have you observed others (such as former teachers, colleagues, college professors, etc.) incorporated this in their teaching and learning practices and/or experienced this in learning of science?
7. What are your expectations for PHYS 7050?
    a. …for the instructor?
    b. … for learning?
    c. …classroom culture?
8. What role has the syllabus for PHYS 7050 played in forming these expectations?

Interview #2 (Follow-up)

The second semi-structured interview will be expected to last 20-30 minutes and take place near the end of the summer semester. The focal point of this interview is to find out about teaching science through conceptual-change based instruction. During these interviews, research participants will be asked to tell the researcher about the key incidents that help them with their understanding of conceptual change-based science teaching. Additionally, students will be questioned about the effect of specific instructional methods identified by the physics faculty on their understanding of conceptual change based science teaching.

1. At this point, what is your ideal view of science teaching and learning?
    a. How does this view compare to the view you shared last time?
    b. How did this course help you to reformulate this view?
    c. In this ideal view, what role do you see the teacher playing and what role do you see the student playing for the best learning to take place?
2. Have there been any changes in your perspective of teaching and learning of physics? If so, what changes?
    a. What aspects of the course were involved in making this change take place?
3. What roles do students' initial ideas play and/or should play in teaching and learning of physics?
    a. In what ways have/would you incorporate/d this in teaching and learning of physics?
    b. What features of the teaching strategies or resources to which you were exposed influenced your thoughts about this?
4. How did the physics faculty model teaching and learning of physics?
    a. How does this help you to reformulate your perspective/view of science teaching and learning? Can you provide an example or two that were influential?
    b. How did the physics faculty identify your initial ideas, value your ideas, and help you further develop your ideas? Provide specific examples
    c. Question the effect of specific strategies the physics professor has identified in prior interviews for teaching conceptual change.
5. Describe your experiences in PHYS 7050 this summer?
    a. What effect did it have on your physics conceptual knowledge?
    b. What effect did it have on your pedagogy for teaching physics?
6. How are physics conceptual knowledge and pedagogy integrated together to you?
    a. How did PHYS 7050 figure into how you see this integration?
    b. What is a specific example of this integration that you saw in PHYS 7050?
7. What is one key idea you will be taking and applying from the course?
8. How well did the syllabus match the course?

9. If we were to re-design this course, what recommendations would you have for that re-design?

APPENDIX E

RESEARCH QUESTIONS/DATA COLLECTION MATRIX

Title: The impact of collaboration between science and education faculty members on teaching for conceptual change: A phenomenographic case study of a physics professor.

Research Question: How does a physics professor conceptualize and practice teaching for conceptual change during and beyond an extended collaboration focused on teaching for conceptual change with a science education professor?

Related Sub-questions	Physics Professor Interview	Classroom Observations	Students Interviews	Unobtrusive Data (Artifacts)	CBAM Instruments
1. What is the evidence of change in a physics professor's conceptions of teaching for conceptual change?	P	S		S	S
1. What is the evidence of change in a physics professor's practices of teaching for conceptual change?	P	S	S	S	S
2. What are the learning-environment characteristics identified by the physics professor that either facilitated or hindered changes in his conceptions and/or practices in teaching for conceptual change?	P	S	S		S

APPENDIX F

ANNOTATED RTOP (SHORT-FORM)

Annotated RTOP

1. were not evident.

2 were limited in quantity and/or quality.

3. were evident, sufficient in quantity and/or quality, and with few exceptions, were appropriate to the teaching and learning context.

4. were evident, were sufficient in quantity and/or quality, and without exception, were highly appropriate to the teaching and learning context.

5. were evident, were sufficient in quantity and/or quality, and without exception, were highly appropriate to the teaching and learning context, and strongly engaged and/or involved all students in learning

Lesson Design	Content (what is) Propositional Knowledge	Content (how to) Procedural Knowledge	Classroom Culture	Student Teacher Relationships
	This section focuses on the level of significance and abstraction of the content, the teacher's understanding of it, and the connections made with other disciplines and with real life**.**	This section focuses on the kinds of processes that students are asked to use to manipulate information, arrive at conclusions, and evaluate knowledge claims. It most closely resembles what is often referred to as mathematical thinking or scientific reasoning.	Communicative interactions in a classroom are an important window into the culture of that classroom. Lessons where teachers characteristically speak and students listen are not reformed. It is important that students be heard, and often, and that they communicate with one another, as well as with the teacher. The nature of the communication captures the dynamics of knowledge construction in that community.	
1. The instructional strategies and activities respected students' prior knowledge and the preconceptions inherent therein.	***6. The lesson involved fundamental concepts of the subject.*** The emphasis on fundamental concepts indicates that there	**11. Students used a variety of means (models, drawings, graphs, symbols, concrete materials, manipulatives, etc.) to represent phenomena.**	**16. Students were involved in the communication of their ideas using a variety of means and media.** The intent of this item is to reflect the communicative	***21. Active participation of students was encouraged and valued***. This implies more than just a classroom full of active

A cornerstone of reformed teaching is taking into consideration the prior knowledge that students bring with them. The term "respected" is pivotal in this item. It suggests an attitude of curiosity on the teacher's part, an active solicitation of student ideas, and an understanding that much of what a student brings to the mathematics or science classroom is strongly shaped and conditioned by their everyday experiences. *This item contains elements of appreciating and enhancing diversity.* ***Assessments of students' prior knowledge, solicitation of students' ideas, and/or discussion of students' preconceptions…***	were some significant scientific or mathematical ideas at the heart of the lesson. For example, a lesson on the multiplication algorithm can be anchored in the distributive property. A lesson on energy could focus on the distinction between heat and temperature. ***Fundamental concepts at the heart of the lesson …***	Multiple forms of representation allow students to use a variety of mental processes to articulate their ideas, analyze information and to critique their ideas. A "variety" implies that at least two different means were used. Variety also occurs within a given means. For example, several different kinds of graphs could be used, not just one. ***Multiple forms of representation that allow students to articulate their ideas, analyze information and/or critique their ideas****…*	richness of a lesson that encouraged students to contribute to the discourse and to do so in more than a single mode (making presentations, brainstorming, critiquing, listening, making videos, group work, etc.). Notice the difference between this item and item 11. Item 11 refers to representations. This item refers to active communication**.** ***Communicative interactions and richness that encouraged students to participate in classroom discourse using more than one mode of participation****…*	students. It also connotes their having a voice in how that activity is to occur. Simply following directions in an active manner does not meet the intent of this item. Active participation implies agenda setting as well as "minds-on" and "hands-on**."** ***Active encouragement and communicating the value of student participation…***
2. The lesson was designed to engage students as members of a learning community. Much knowledge is socially constructed. The setting within which this occurs has been called a "learning community." The use of the term community in the phrase "the scientific community" (a "self-governing" body) is similar to the way it is intended in this item. Students participate actively, their participation is integral to the actions of the community, and knowledge is negotiated within the community. It is important to remember that a group of learners does not necessarily constitute a "learning community." *This item contains elements of appreciating and enhancing diversity**.***	**7. The lesson promoted strongly coherent conceptual understanding.** The word "coherent" is used to emphasize the strong inter-relatedness of mathematical and/or scientific thinking. Concepts do not stand on their own two feet. They are increasingly more meaningful as they become integrally related to and constitutive of other concepts. ***Clear identification of and emphasis on important concepts and their inter-relatedness…***	**12. Students made predictions, estimations and/or hypotheses and devised means for testing them.** This item does not distinguish among predictions, hypotheses and estimations. All three terms are used so that the RTOP can be descriptive of both mathematical thinking and scientific reasoning. Another word that might be used in this context is "conjectures." The idea is that students explicitly state what they think is going to happen before collecting data. ***Students' predictions, estimations and/or hypotheses and means for testing them…***	**17. The teacher's questions triggered divergent modes of thinking.** This item suggests that teacher (*or student*) questions should help to open up conceptual space rather than confining it within predetermined boundaries. In its simplest form, teacher questioning triggers divergent modes of thinking by framing problems for which there may be more than one correct answer or framing phenomena that can have more than one valid interpretation. ***A variety of questions that enhanced divergent modes of thinking*** *…*	**22. Students were encouraged to generate conjectures, alternative solution strategies, and/or different ways of interpreting evidence.** Reformed teaching shifts the balance of responsibility for mathematical and scientific thought from the teacher to the students. A reformed teacher actively encourages this transition. For example, in a mathematics lesson, the teacher might encourage students to find more than one way to solve a problem. The encouragement would be highly rated if the whole lesson was devoted to discussing and critiquing alternative solution strategies**.**

Participation of students as members of a learning community in which students share their knowledge and ideas, and negotiate their understandings…				***Active encouragement and communicating the value of student participation…***
3. In this lesson, student exploration preceded formal presentation. Reformed teaching allows students to build complex abstract knowledge from simpler, more concrete experience. This suggests that any formal presentation of content should be preceded by student exploration. This does not imply the converse…that all exploration should be followed by a formal presentation**.** ***Development of students' knowledge moving from concrete experiences to more abstract knowledge and/or student exploration of content before formal presentation/discussion***…	**8. The teacher had a solid grasp of the subject matter content inherent in the lesson.** This indicates that a teacher could sense the potential significance of ideas as they occurred in the lesson, even when articulated vaguely by students. A solid grasp would be indicated by an eagerness to pursue students' thoughts even if seemingly unrelated at the moment. The grade level at which the lesson was directed should be taken into consideration when *assessing* this item ***The eager pursuit and potential significance of students' thoughts and ideas…***	**13. Students were actively engaged in thought-provoking activity that often involved critical assessment of procedures.** This item implies that students were not only actively doing things, but that they were also actively thinking about how what they were doing could clarify the next steps in their investigations. ***Student participation in thought-provoking activity that involved critical assessment of procedures***…	**18. There was a high proportion of student talk and a significant amount of it occurred between and among students.** A lesson where a teacher does most of the talking is not reformed. This item reflects the need to increase both the amount of student talk and talk among students. A "high proportion" means that at any point in time it was as likely that a student would be talking as that the teacher would be. A "significant amount" suggests that critical portions of the lesson were developed through discourse among students. ***A high proportion and significant amount of student talk during the lesson…***	***23. In general the teacher was patient with students.*** Patience is not the same thing as tolerating unexpected or unwanted student behavior. Rather there is an anticipation that, when given a chance to play itself out, unanticipated behavior can lead to rich learning opportunities. A long "wait time" is a necessary but not sufficient condition for rating highly on this item. *This item contains elements of appreciating and enhancing diversity*. ***Patience for the development of students' contributions and ideas…***
4. This lesson encouraged students to seek and value alternative modes of investigation or of problem solving.	**9. Elements of abstraction (i.e., symbolic representations, theory building) were encouraged when it was important to do so.**	**14. Students were reflective about their learning.** Active reflection is a meta-cognitive activity that facilitates learning. It is sometimes referred to as	**19. Student questions and comments often determine the focus and direction of classroom discourse.** This item implies not only that the flow of the lesson was often	**24. The teacher acted as a resource person, working to support and enhance student investigations.** A reformed teacher is not there to tell students what to do and

Divergent thinking is an important part of mathematical and scientific reasoning. A lesson that meets this criterion would not insist on only one method of experimentation and one approach to solving a problem. A teacher who valued alternative modes of thinking would respect and actively solicit a variety of approaches, and understand that there may be more than one answer to a question. *This item contains elements of appreciating and enhancing diversity.* ***Solicitation and respect for a variety of modes of divergent thinking, multiple methods of experimentation and/or problem solving and different answers to questions…***	Conceptual understanding can be facilitated when relationships or patterns are represented in abstract or symbolic ways. Not moving toward abstraction can leave students overwhelmed with trees when a forest might help them locate themselves. ***Symbolic representations and abstractions to represent relationships and/or patterns among content and/or concepts****…*	"thinking about thinking." Teachers can facilitate reflection by providing time and suggesting strategies for students to evaluate their thoughts throughout a lesson. A review conducted by the teacher may not be reflective if it does not induce students to *re-examine* or *re-assess* their thinking. ***Allocated time and suggestions for students to be reflective about their thinking and to evaluate their thoughts****…*	influenced or shaped by student contributions, but, that once a direction was in place, students were crucial in sustaining and enhancing the momentum. ***A focus and direction of the lesson determined by student questions and comments****…*	how to do it. Much of the initiative is to come from students, and because students have different ideas, the teacher's support is carefully crafted to the idiosyncrasies of student thinking. The metaphor "guide on the side" is in accord with this item. ***Teacher support for, and enhancement of student initiatives in investigative thinking …***
5. The focus and direction of the lesson was often determined by ideas originating with students. If students are members of a true learning community, and if divergence of thinking is valued, then the direction that a lesson takes cannot always be predicted in advance. Thus, planning and executing a lesson may include contingencies for building upon the unexpected. A lesson that met this criterion might not end up where it appeared to be heading at the beginning. ***Student thinking and/or ideas that determined the focus and direction of lesson content and/or teaching and learning activities…***	**10. Connections with other content disciplines and/or real world phenomena were explored and valued.** Connecting mathematical and scientific content across the disciplines and with real world applications tends to generalize and make it more coherent. A physics lesson might connect with the role of electricity in biological systems, or with the wiring systems of a house. A mathematics lesson on proportionality might connect with the nature of light, and refer to the relationship between the height of an object and the length of its shadow. ***Exploration and the value of connections between the subject matter and other***	**15. Intellectual rigor, constructive criticism, and the challenging of ideas were valued.** At the heart of mathematical and scientific endeavors is rigorous debate. In a lesson, this would be achieved by allowing a variety of ideas to be presented, but insisting that challenge and negotiation also occur. Achieving intellectual rigor by following a narrow, often prescribed path of reasoning, to the exclusion of alternatives, would result in a low score on this item. Accepting a variety of proposals without accompanying evidence and	**20. There was a climate of respect for what others had to say.** Respecting what others have to say is more than listening politely. Respect also indicates that what others had to say was actually heard and carefully considered. A reformed lesson would encourage and allow every member of the community to present their ideas and express their opinions without fear of censure or ridicule. *This item contains elements of appreciating and enhancing diversity.* ***A climate of respect in which students could present their***	***25. The metaphor "teacher as listener" was very characteristic of this classroom.*** This metaphor describes a teacher who is often found helping students use what they know to construct further understanding. The teacher may indeed talk a lot, but such talk is carefully crafted around understandings reached by actively listening to what students are saying. "Teacher as listener" would be fully in place if "student as listener" was reciprocally engendered. *This item contains elements of appreciating and enhancing diversity.*

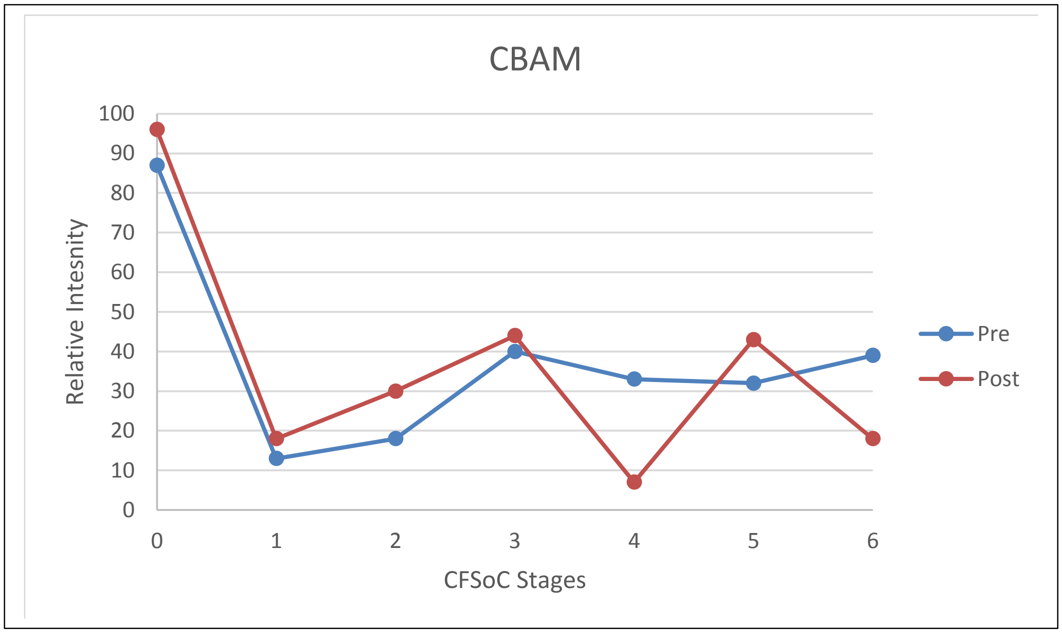
	content disciplines and/or real world connections*…*	argument would also result in a low score. ***A variety of ideas, challenge and negotiation of knowledge among students, and intellectual rigor…***	***ideas and express their opinions…***	***Active listening to students and assisting them to construct further understandings…***

APPENDIX G

CBAM RESULTS AND ANALYSIS

Stages of Concerns (SoC) Instrument

CBAM Results



The physics professor' concern profile based on the Stages of Concern Questionnaire (SoCQ) is shown in figure. The SoC instrument defines seven levels of progression: awareness, informational, personal, management, consequence, collaboration, and refocusing (indicated on the profile as stages 0-6, respectively). Professor Thomson's peak in Stage 0 (awareness) on both of the pre and post profiles indicates that he has a lot of other competing concerns on his mind besides the innovation (design of class for teaching conceptual change). In the preliminary profile, the second peak at stage 3 (management) indicates a high concern about the logistics, time, and managerial challenges of a being a facilitator of the change. The tailing up of the profile to stage 6 (refocusing) implies that Professor Thomson has his own ideas that he sees as having potentially as much or more merit than the innovation as currently being defined. The post profile again shows a primary peak at stage 0 (awareness) indicating the competing concerns Professor Thomson has with the innovation. Likewise, the secondary peak at stage 3 (management) shows continue concerns with the managing of the innovation. However, several key differences emerge. The sharp valley at stage 4 (consequence) shows less concern about the relevance of the innovation for the students and a need to evaluate student outcomes and consequently increase student outcomes. The secondary peak at stage 5 (collaboration) indicates more concern about coordination and cooperation with others in the use of the innovation. Finally, the tailing off at stage 6 shows Professor Thomson is no longer holding onto competing ideas to the innovation as indicated in the preliminary profile (Hall et al., 1998).

APPENDIX H

TEACHER STRATEGIES SURVEY INSTRUMENT

Survey Form for the Study 'An Investigation of the of the Approaches Used by Pre-Service Science Teachers in Responding to Students' Ideas about Scientific Phenomena'

A. Personal Information

1. Name: ___________________________

2. Undergraduate degree(s) in: ___________________________

   ____

3. Institution(s) granting degree: ___________________________

   ____

4. Graduate degree(s) in: ___________________________

   ____

5. Institution(s) granting degree: ___________________________

   ____

6. Length of time in MAT program: _________

7. Education coursework taken in program: ___________________________

   ____

   ____

   ____

   ____

____

8. Description of teaching experiences: __________________________

   [subjects taught & grade levels, length of __________________________

   time; include informal experiences (e.g. work __________________________

   at museum) and field experiences in program] __________________________

9. Best memories of your own experiences with learning science (e.g. What was your favorite high-school / college science class and what made it such a good class?):

B. Prompts about Teaching Practices

All of us who teach science are all aware that students come into our classrooms with ideas about phenomena that are different from the scientific ideas we would like them to learn; our teaching practices must respond to

this aspect of students' prior knowledge . . .

(1) Where do you think these ideas which students have that are different from those of science come from? i.e. What is the origin of these ideas?

(2) Please describe the teaching strategy(ies) you think should be used to respond to student ideas which are different from those of science and to help students better understand the phenomena related to those ideas.

(3) Please provide a specific example(s) of what this strategy(ies) might look like 'in action' using a specific concept from the science discipline with which you are most comfortable.

(4) Describe what it is about this strategy(ies) that you think make it effective at allowing a teacher to respond to students' ideas which are different from those of science and at helping students learn about scientific phenomena.

(5) Below is an excerpt from an actual physics lesson being conducted with high-school students. As the opening line in the dialogue indicates, the teacher had just shown the class a video related to forces and motion. Among the examples of these concepts presented in the video, the forces involved in the various motions of a bicycle were examined. The discussion in the class picks up with the teacher trying to review the ideas presented in the video. Please read the dialogue carefully and then answer the questions which follow the excerpt.*

1. Teacher: The video has been about forces that act when cycling. Well, here [points to the glider on the track] I have a kind of bicycle. Let me now first ask what forces are acting on it. Just try: What forces do you think are acting at this moment? Are there any forces acting?
2. Eric: Gravity.
3. Teacher: Gravity, Eric says. What if gravity were the only force, what would happen then?
4. Eric: Then it would go down.
5. Teacher: Then it would go down. Ernie, what other forces could be acting?
6. Ernie: Eh . . . well. . .
7. Teacher: What prevents it from falling down?
8. Ernie: The track.
9. Teacher: Right, the track. So the track has to supply a counterforce to prevent the glider from falling down. Just for the sake of completeness: Eric, which direction has gravity?
10. ?:[joking] Upwards.
11. Eric: No, downwards.
12. Teacher: So, Orson, the force of the track is upwards. Right?
13. Jane: How's that?
14. Orson: Well, otherwise it would fall down.
15. Teacher: Otherwise it would fall down, he says. So, if it did not rest on the track and I dropped it, then only gravity would act and it would fall down. If the track wants to stop it, then it will have to push the glider upward.

16. Jane: But the track does not push, does it?
17. Teacher: The track does not push.
18. Jane: No . . .

[*The numbers in front of each speaker's designation is the turn number in the lesson dialogue.]

(a) What is the idea that Jane states in this excerpt that is different from the scientific view?

(b) If you were the teacher, what would you have done following line 18 in order to respond to this idea that Jane has? Provide as much detail as possible including any statements you might have made, questions you might have asked, illustrations you might have provided, etc.

(c) What would be your goal for the actions you described in (b) and how would you know whether you had achieved that goal?

APPENDIX I

DATA REDUCTION TABLE

Iteration	Description	Results
First Pass	Open Coding – earliest interview to most recent	Generated 86 codes
	Generally grouped codes into four general descriptions	Four General Descriptions: Background Teaching for Conceptual Change Personal Conceptions In vivo
	Further refined general descriptions – 5 categories	Five Categories: Background, Teaching for Conceptual Change, Practiced Conceptions In vivo
	Reexamined initial coding and grouped all categories related to conceptual change into 6 grouping	Six Groupings: Teaching Ideas Framework Conceptual Change – Teaching Conceptual Change – Students Conceptual Change - Conceptions
Second Pass	Focused Coding – Teaching for conceptual change Recoded interviews identifying all relevant passages related to conceptual change and teaching for conceptual change	Collated identified passages with NVivo into a 'pool of meaning'
	Alternative pass, identified passages related to changes in the physics professor's conceptions or practices.	Coded these passages by the IMTPG model into: External Domain Personal Domain Domain of Consequences Domain of Practice
Third Pass	Reviewed conceptual change 'pool of meaning' and generated emergent categories of teaching for conceptual change. Divided excerpts into these grouping and began to record the key structural components of each category	Initial Emergent Categories: Didactic Teaching Effective Teaching Students' Ideas Students' Framework Conceptual Framework Modeling
	Discussed methodology and analysis with peer debriefer. Refined categories to be more in line with traditional descriptors. Further delineated within the effective teaching category a focus on	Refined Categories (peer debriefing) Transactional Teaching Active Teaching Focus on Teaching

	informed pedagogy and a focus on teaching evaluated via assessment.	Students' Ideas Students' Learning Framework Conceptual Change Modeling
	Reviewed pool of meaning to further define the categories. Referenced literature (Prosser, Trigwell, & Taylor, 1994) on categories of teaching to contextualize progress. Conducted word frequency analysis on each interview to identify shifts in language over time.	Refined Categories (literature): Transactional Teaching Active Teaching – subdivided Informed Pedagogy Focus on Teaching Students' Ideas (novice) Students' Learning Student Framework (expert) Conceptual Change Modeling
	Initially coded class observational notes indexed with transcripted excerpts from audio recording of PHYS 7050 classes. Identified all related passages to teaching for conceptual change. Reviewed categories after this initial coding of the class observational notes and further refined the categories.	Refined Categories (class observational notes): Transactional Teaching Active Teaching Informed Pedagogy Focus on Teaching Students' Ideas Students' Learning Framework Novice Expert
	Revisited interview excerpts grouped by categories. Reclassified with the updated categories comparing and contrasting the statements to further delineate the categories. Refined categories were then used to code the 'pool of meaning' derived from the class observational notes. The pooled excerpts were used to again refine the categories.	Final Categories: Transactional Teaching Active Teaching Students' Ideas Students' Learning Conceptual Change Novice Expert

APPENDIX J

Example of the Data Analysis Process

To illustrate the data analysis process a key excerpt from one of the different interviews is used to show the coding process and how it led to an important characteristic of the conceptual change category.

Step 1. Open coding of the interview transcripts.

All of the interview transcripts were read. As specific descriptors or patterns emerged, each was assigned a code or label in NVivo. Descriptors using the exact words of the professor were labeled "in vivo" codes.

This example excerpt was from the executional interview (7/31/13). My question (A) and Professor Fairbanks' (B) answer are included for context. A portion of the transcript (highlighted) was coded *Expert vs. Novice,* based on Professor Fairbanks' comparing and contrasting an expert with a student in their understanding of math.

Example Excerpt

A: I guess when you look at introductory classes say the calculus based kind of introductory, …is there's actually even more pressure there for the mathematical framework because you're having a more developed… a higher level…I mean it does integrate with the science at a much higher level and a more in depth level. And so, looking at teaching conceptual change in a class like there, you identify the conflict. I was just wondering is it even more pronounced in something like that?

B: Yeah. No, it is because, you have the same issues that come up in modern physics so you expect them to use that high level of mathematics to do that, but they, um—you're using these mathematical tools which if they really have a deep understanding of because we get to-as you get to more expert then in some sense it's not as abstract…

A: Okay. Yeah.

B: … When it's—if you're integrating to do the area under a curve or taking a derivative to get a slope and you have a real fundamental understanding of physically what does this equation represent…

A: Hm-hmm [affirmative].

B: …why am I doing this operation, what does it represent? Then you're thinking of it in a much more concrete way…

A: Hm-hmm [affirmative].

B: …whereas if the students don't have that understanding, then it's very abstract to them because they're following a procedure and they're saying, okay we take the equation, we do this, and then you do this, and they don't really understand why they're doing those procedure…

A: Yeah.

B: …and so to them it's a procedure, it's an abstract. In the end, it's what plops out some number…

A: Yeah.

B: …and they haven't connected the physical nature, what the mathematics actually represents. And so those issues are linked there because some of the - as an expert, some of your conceptual understanding comes through those advanced mathematical tools…

A: Yeah.

B: …because you've attached the physical meaning to them of what you're doing when you do this mathematical operation and…

A: Yeah.

B: …you have a picture in your head of what you're doing, just to the level of looking at graphs of a two dimensional function, whereas you can look at that and interpret it and glean information from it and-and manipulate it in your head as a physical entity…

A: Yeah.

B: …and students, you know, half of them…

A: The abstract dots.

B: …it's an abstract dot because they have no idea how to-what they're doing there so…

Step 2. Grouping of initial coding into general categories.

After the initial coding, the codes were grouped under four general descriptors: Background, Teaching for Conceptual Change, Personal Conceptions, and In Vivo. The example excerpt was placed in the Teaching for Conceptual Change descriptor.

Step 3. Focused coding.

A second reading of all the interview data was done as a focused coding for teaching for conceptual change. All of the passages identified in this coding were collated in NVivo to form a "pool of meaning". An alternative pass of the data in a focus coding for the IMTPG model was also done where passages were coded for their connection to the IMTPG four domains: External Domain, Personal Domain, Domain of Consequences, and Domain of Practice.

Step 4. Coding the "pool of meaning".

The third coding pass focused on coding the "pool of meaning" into emergent categories of teaching for conceptual change. Initially six categories emerged: Didactic Teaching, Effective Teaching, Students' Ideas, Students' Framework, Conceptual Framework, and Modeling. These category titles were a combination of In Vivo phrases used by Professor Fairbanks and general descriptors. Excerpts for each category were collated in NVivo and then analyzed identifying key characteristics of each category.

Step 5. Refined categories through peer debriefing.

During this time a large portion of the "pool of meaning" was shared with my peer debriefer to code on his own. We then met and discussed our emergent coding. Subsequently, the categories were refined and expanded into eight categories: Transactional Teaching, Active Teaching, Focus on Teaching, Students' Ideas, Students' Learning, Framework, Conceptual Change, and Modeling. The "pool of meaning" was again reviewed in an iterative process guided by the refined categories. The grouping of the related excerpts in each category further delineated the categories.

Step 6. Refined categories by contextualizing progress with referenced literature.

To contextualize the process, Prosser, Trigwell, & Taylor's (1994) categories of teaching conceptions were consulted. This led to further delineating of Active Teaching into an Informed Pedagogy and Focus on Teaching level and associating the Students' Ideas category with a novice view and the Student Framework with a more expert view.

At this point, the example excerpt was classified in the Framework category which had been divided into a novice and expert level. At the novice level, a distinguishing characteristic was *the framework was seen as abstract ideas*. Another excerpt taken from the Planning Interview (6/12/2013) was listed to illustrate this.

> How do people change their conceptual framework?…Then there's the theoretical background. So, Professor Crefeld was doing some of that and a lot of what overlapped between the things he would talk about and the kind of things we'd be doing as we worked on the specifics was the, the general ideas of how you get students to see a

dissidence between their framework and what actually happens. Or different pieces of their framework not making sense together, and then forcing them to engage those things so that then they have to find some way to resolve that conflict. (Interview, June 12, 2013)

The imprecise language and hesitation in this excerpt were tagged to show how Professor Fairbanks' conceptions on teaching for conceptual change were still abstract. To further emphasize this, the previous excerpt of Professor Fairbanks' description of a Mathematical expert was highlighted to compare and contrast.

In the expert level, a section of the example excerpt was referenced to highlight the point that an expert's view of framework is much more concrete and less abstract.

> As you get to more expert then in some sense, it's not as abstract… When it's—if you're-you're integrating to do the area under a curve or taking a derivative to get a slope and you have a real fundamental understanding of physically what does this equation represent? Why am I doing this operation, what does it represent? Then you're thinking of it in a much more concrete way. Whereas if the students don't have that understanding, then it's very abstract to them because they're following a procedure. (Interview, July 31, 2013)

Step 7. Defined categories used to integrate the Class Observation Notes with the Class Audio Recordings into Integrated Observation Notes.

These refined categories were used to review the class observational notes, marking relevant descriptors in the class. For each marked section, the corresponding audio recordings of the classes were transcribed and inserted into the class observational notes creating a set of Integrated Class Observation Notes.

Step 8. Coding of Integrated Observation Notes and creation of "pool of meaning".

These integrated observation notes were then coded for the refined categories and the coded excerpts were added to the interviews' "pool of meaning" for each category. These expanded "pools of meaning" were reanalyzed and used to refine the emergent categories into their final form. The final categories were further delineated by comparing and contrasting the excerpts in each category to distinguish the key characteristics of each category.

As the class observational excerpts were added, the categories were further refined. In this iteration of the categories (version 5), the example excerpt was referenced in the Framework- Expert category under the characteristic of *difference between novice and expert views (mathematical example)*

> You're using these mathematical tools which if they really have a deep understanding of- because we get to—as you get to more expert then in some sense, it's not as abstract. Right When it's—if you're integrating to do the area under a curve or taking a derivative to get a slope and you have a real fundamental understanding of physically, what does this equation represent? Why am I doing this operation, what does it represent? Then you're thinking of it in a much more concrete way. Whereas if the students don't have that understanding, then it's very abstract to them because they're following a procedure and they're saying, okay we take so here's the thing, we take the equation, we do this, and then you do this, and they don't really understand why they're doing those procedures and so to them it's a procedure,… it's an abstract dot. (Interview, July 31, 2013)

In this refining pass, the idea from the excerpt comparing and contrasting the concrete way of the expert with the abstract way of the novice emerges and was connected with Professor

Fairbanks' description of his teaching of conceptual change from the "concrete to the abstract". Examining this connection showed that in the example excerpt, on applying mathematical theory to graphs, Professor Fairbanks was describing the difference between a novice and expert view of a framework. This is illustrated below in the two excerpts,

> "You're using these mathematical tools which if they really have a deep understanding of…more expert then in some sense, it's not as abstract" (Interview, July 31, 2013).

> If you're integrating to do the area under a curve or taking a derivative to get a slope and you have a real fundamental understanding of physically, What does this equation represent? Why am I doing this operation, what does it represent? Then you're thinking of it in a much more concrete way. Whereas if the students don't have that understanding, then it's very abstract to them because they're following a procedure and they're saying, okay we take the equation, we do this, and then you do this, and they don't really understand why they're doing those procedures and so to them it's a procedure, it's an abstract dot. (Interview, July 31, 2013)

Step 9. Further delineation of the emergent categories through an iterative analysis.

Professor Fairbanks, in these excerpts, provided in his own words a way to distinguish a novice view from an expert view. His working definition was then used in reexamining his own conceptions about teaching for conceptual change. Professor Fairbanks' views on teaching for conceptual change from the Planning Interview (July 10, 2013) were compared and contrasted with the Executional Interview (July 31, 2013).

> I think the lack of a little more coherent presentation of the conceptual change ideas is lacking a little bit. I mean I'm trying to do a little bit better but I can't make up for that really. I can't successfully take that role totally. (Interview, July 10, 2013)

> It went from content and analyzing the content to the close look of, in this particular circumstance, what are we trying to accomplish? So, they were learning about teaching conceptual change in the context of this worksheet - motion diagrams. Doing that and then the bigger picture kind of came in later. (Interview, July 31, 2013)

This illustrated Professor Fairbanks' progression in his conceptions from a novice view to a more expert view. This idea was then extended to his practices of teaching for conceptual change of abstract to concrete. "But instead of getting that framework first, which actually is the rule of thumb in physics teaching is, you go from the concrete to the abstract not the other way around. So, I guess we followed that in general" (Interview, July 31, 2013). All of the above illustrated the process of defining and delineating the emergent categories.

Step 10. Using the emergent categories to distinguish the evidence of change in the physics professor's conceptions and practices through the timeframe of the collaboration.

After the emergent categories were fully characterized, these were used to position where the Physics Professor was in his conceptions and practices for teaching for conceptual change throughout the collaboration. Characteristics of the physics professor's conceptions and practices were defined for six distinct time periods of the study: preliminary, initial collaboration, planning, independent practice, resumed collaboration, and extended practice,

APPENDIX K

PERIODS OF STUDY

Evidence Summary of Physics Professor's Conceptions and Practices of Teaching for Conceptual Change

Period	Time Period	Evidence	
Preliminary	6/5-19/2012 Interview 6/5/2012	Conceptions	Valued student ideas – ideas not wrong, limiting Teaching directly responsive to where the students are Creating conflict between students' ideas and how things work Need for students to develop alternative theory
	Classes 1-5 (2012)	Practice	Establishing a safe environment for students to 'take a risk and expose their misconceptions' Predictions are never wrong. They're just a prediction (valuing of student ideas) Switching the perspective of instruction from the role of the student to the perspective of the teacher Shift students' focus from grades to sharing their thinking Students struggling on their own through the concepts The role of discussion in helping the students' ideas emerge Increase the students' abilities to connect the theory with their actual teaching Connecting the theory provided by science education professor with the practice of learning physics. Adopting the specific vocabulary of conceptual change as modeled by science education professor Instructing and modeling pedagogy on teaching for conceptual change. Tension between instruction and modeling.
Initial Collaboration	6/21–7/23/2012 Interview 7/23/2012	Conceptions	Focusing on underlying framework of why students think what they do. Underlying framework evaluate effectiveness and how to think about student's experience Stronger valuing and emphasizing how students' ideas form Students talk about not just what their ideas are but why Students are aware of their thinking in their model (metacognition)

	Classes 6-14 (2012)	Practice	Influence of science education professor's instruction. Time for students to compare their ideas against the new idea, letting them see the plausibility of the new idea Tension between teaching content, modeling the correct teaching, and giving them practice at leading the activity Recognizing a reverting to direct instruction when time pressure felt. Discussion solicited students' ideas, drew out student thoughts on potential misconceptions of students, launched into lecture (Limited classroom discussions focused on students' ideas)
Planning	6/11-13/2013 Interview 6/12/2013	Conceptions	Value of students struggling with their ideas Engaging students in open discussion where students struggle with their ideas. More developed theoretical framework for conceptual change Limited confidence in teaching conceptual change Framework used to gauge what is most successful in bringing about conceptual change (Evaluating pedagogy through lens of framework)
	Classes 1-2 (2013)	Practice	Understanding where students are, enabling them to understand where they are, let them engage their ideas, and resolve their conflicts. (Greater articulation of conceptual change process) Greater emphasis on students' engaging their ideas Prevalence of students' preconceptions, robust nature 'Know most of the ideas doesn't mean you know how to present them' (Difference between conceptions and practice) Reluctance to fully engage in teaching the theoretical framework of conceptual change. Tension between instruction and modeling. (Student-centered vs teacher-centered)
Independent Practice	6/18-7/10/2013 Interview 7/10/2013	Conceptions	Teaching conceptual change starting from concrete example to the theoretical (Integrating of framework into pedagogy) Students' ideas revealed so students can work with their ideas Teachers sets up situation where students recognize conflict in their ideas. Theoretical framework of students established through discussions on activities.

			(Greater emphasis on developing student framework) Lack of confidence in teaching theoretical framework of conceptual change Shifting from inward focus on his confidence as an expert to outward focus on students developing their ideas.
	Classes 3-8 (2013)	Practice	Reluctance to directly teach and lead discussion on theory of conceptual change Drew key elements of conceptual change out through discussion, questioning of students. Shifting focus from students' ideas to students' framework Historical example of Aristotle - Newton used to show conceptual change process (Using concrete example to show theory) Moderated class discussions showed improving ability to facilitate class discussions drawing out students ideas and having them evaluative their ideas Using concrete examples to demonstrate teaching for conceptual change Lab activity on how conceptual change framework informed writing of pedagogy (Making the tacit knowledge of the pedagogy more visible). Increase in his explicit use of conceptual change vocabulary Direct instruction under time pressure, tension between modeling and preparing students.
Resumed Collaboration	7/16-31/2013 Interview 7/31/2013	Conceptions	Reflecting on his role In discussions, recognizing when shifting into other modes (Metacognition of his teaching) Focus on framework development Framework made of interconnected ideas and used as foundation to reason from Students thinking about the consequences of their ideas (Importance of metacognition in changing framework) Evolving idea of context-dependent ideas forming stable frameworks.
	Classes 9-12 (2013)	Practice	Connecting instruction to ideas presented by science education professor, active engagement with science education professor's instruction (Collegiality of collaboration)

			Moderated class discussions soliciting students' ideas, led student to refine and evaluate their ideas to develop a more consistent framework. Greater ambiguity in discussions allowing students the space to wrestle with ideas. (More student focused) 'Ideas aren't in isolation', importance of exploring ideas in different contexts to develop consistent framework Both emulation and assimilation of science education professor's instruction. Assimilation of moderated class discussions as effective tool for modeling teaching conceptual change Limits in engaging student metacognitively and consistently integrating framework of conceptual change throughout his instruction
Extended Practice	10/2-9/2013 Interview 10/9/2013	Conceptions	Changing students' approach to labs (framework) start thinking of the process and learning (metacognition) Evaluating understanding of models Designing course around experiments acting as discrepant events to evaluate models Vagueness of language describing goals and focus of class. Ideas of filling knowledge gaps
	Classes (PHYS 3000) 10/2/2013 & 10/7/2013	Practice	Assessed the background of the students to determine his starting point Limited moderated discussions Investigation used as discrepant event Conceptual change seen in envisioning the class and evaluating his teaching. Instruction in class focused on informing students. Direct instruction most prevalent teaching technique.

APPENDIX L

WORD COUNT FREQUENCY ANALYSIS OF INTERVIEWS

Initial		Post		Planning		Instructional		Executional		Followup	
Word	Count	Word	Count	Word	Count	Word	Count	Word	Count	Word	Count
idea	14	idea	8	idea	10	idea	12	idea	15	idea	3
ideas	12	ideas	8	ideas	24	ideas	16	ideas	45	ideas	5
misconceptions	10	misconceptions	7			misconceptions	4	misconceptions	7		
misconception	4										
		discussion	2			discussion	7	discussion	4		
		discussions	2	discussions	9	discussions	7	discussions	10		
		framework	6	framework	13	framework	8	framework	29	framework	5
				understanding	20	understanding	13	understanding	11	understanding	8
				change	36	change	21	change	23	change	9
				changes	12	changes	3	changes	3		
						changed	4				
				time	24	time	20	time	12	time	26
				question	7	question	8	question	4	question	5
						questions	11			questions	23
						context	4	context	3	context	3
						connect	4	connect	3	connect	10
								connected	5		
								connecting	3		
								connections	3	connection	3
								explicitly	3		
										explicit	3
						expert	8	expert	6		
								struggle	11		
								distracters	3		
								metacognitive	3		
										transmission	5